ELECTRICAL AND COMPUTER ENGINEERING DEPARTMENT

(2)

FINAL SCIENTIFIC REPORT

on

Contracts ONR N00014-80-C-0063
and ONR N00014-88-K-0174

"Investigation of RF Emissions From Electric Field Dominated Plasmas"

January 1, 1980 to March 31, 1989

J. Reece Roth
Principal Investigator

UNIVERSITY OF TENNESSEE

KNOXVILLE
TN 37996-2100

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ABSTRACT

This final report describes basic research at the UTK Plasma Science Laboratory which was supported by Office of Naval Research contract ONR-N00014-88-K-0174, and by its predecessor contract, ONR-N00014-80-C-0063. During this 9.25 year period, eight archival scientific papers were published, and 31 oral or poster papers were presented, most at the annual APS and IEEE Plasma meetings. These contracts also supported four graduate theses, approximately 18 person-years of half-time GRA research and training, and the preparation of 9 routine reports to the Navy, including three trip reports on overseas lab visits and/or attendance at international plasma conferences.

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19. Abstract (Continued)

Accomplishments during this 9 year period including building up the UTK Plasma Science Laboratory into a major academic center of plasma science research in the southeastern quadrant of the United States, which now has an annual budget of approximately $300,000. In addition to being the founding support which allowed us to establish this laboratory, the Navy contracts covered by this report also provided the continuity necessary to train students and build the plasma science effort at the University of Tennessee up to its present level. Our research accomplishments include a number of items which were the first to be done anywhere. These include the initial two year effort to confirm the theory of the geometric mean plasma emission, which was jointly discovered by the Principal Investigator and Prof. Igor Alexeff of UTK. This process results from two interpenetrating electron beams in a Penning discharge. This work was published under Navy auspices in the Physics of Fluids. After confirming our theory, the plasma emissions due to this phenomena were measured quantitatively.

Throughout the 9.25-year period of this contract, continuing efforts were made on diagnostic and software development for the study of plasma turbulence, automatic reduction of Langmuir probe data, and correlation studies of plasma fluctuations and turbulence using digital time series analysis techniques based on the fast Fourier transform. Most recently, we have applied the methods of chaos theory to the investigation of plasma turbulence, using a commercially available software program.

In the last five years of this contract, extensive studies were conducted of fluctuations in our highly turbulent Penning discharge. By perturbing the plasma with a signal of known amplitude and frequency applied to an "effector probe", we were able to demonstrate the enhancement of plasma turbulence and the resulting turbulent heating of the plasma electron and/or ion population. More interestingly, these active modification experiments also demonstrated conditions under which a low frequency modulation of the plasma by the effector probe could dampen the turbulent modes present in the unmodulated plasma. The damping of turbulent modes at higher frequencies, above 50 kilohertz, was as high as 10 to 20 db in some instances. This suggests a way to actively modify plasma turbulence and affect or reduce transport parameters which depend on the level of plasma turbulence.

Finally, we developed a diagnostic procedure for measuring the effective collision frequency of electrons in plasmas due not only to binary collisions with other electron or neutral atoms, but also to turbulent collisions of the electrons which result when the electrons scatter off fluctuating electric fields in our plasma. This diagnostic method is based on the broadening of the resonance at the electron gyrofrequency. The broadening of this absorption line is a function of the effective collision frequency, and its measurement with our network analyzer allows us to make a direct experimental measurement of the effective collision frequency in the plasma. We have shown that the effective collision frequency in this highly turbulent plasma can be as much as 20 times that expected from electron-neutral collisions, the dominant binary collisional process in this plasma.

Report PSL 89-1

Final Scientific Report

on

INVESTIGATION OF RF EMISSIONS FROM ELECTRIC FIELD DOMINATED PLASMAS

for the period
January 1, 1980 to March 31, 1989

Submitted to

THE OFFICE OF NAVAL RESEARCH

by

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for

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UTK Plasma Science Laboratory
Report PSL 89-1

March 31, 1989

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Principal Investigator

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EXECUTIVE SUMMARY

Background Information

This document describes a just-completed 9.25-year program of research at the University of Tennessee's Plasma Science Laboratory, which is located on the Knoxville campus, and affiliated with the Electrical and Computer Engineerng Department. Our Laboratory specializes in the experimental investigation of interactions between RF radiation and plasmas, and in research in electric field dominated, steady-state plasmas. These plasmas exhibit several unique characteristics: very high levels of plasma turbulence; broad-band radio frequency emission; ion kinetic temperatures up to several kilovolts; ion kinetic temperatures much higher than that of the electron population; and strong axial and radial electric fields, measured values of which have been in excess of several hundred volts per centimeter along the magnetic field. The presence of strong electric fields in the plasma allows work from external sources to be done on the plasma, thus affecting its confinement, heating, and transport properties. Such electric field dominated plasmas can achieve high energy densities, and are of potential utility in such applications as lasers, pulsed broad-band radio frequency emitters, high power sub-millimeter microwave emission, communications, and directed energy weapons.

The level of effort on this contract during its 9.25 year duration is summarized on Table I. This contract was renewed at approximately one year intervals in response to successive proposals. These proposals followed up interesting results which appeared during the course of our exploratory research program. The initial year of this program covered calendar year

1980. This was followed by a 9 month extension until October 1, 1981, after which the contract was renewed at one year intervals until the final 18-month period, from October 1, 1987 to March 31, 1989. The 7.75 year initial period of this research program, until September 30, 1987, was covered by ONR contract N00014-80-C-0063. The final 18 months of this research program, which ends on March 31, 1989, were covered by ONR contract N00014-88-K-0174. The last, 18-month contract was for a period of one year which ended on September 30, 1988, with a no cost extension to March 31, 1989, in order to cover the preparation of this final report and completion of two theses which were still in progress as of September 30, 1988. This contract supported the Principal Investigator for one quarter time during the entire duration of the contract. It also supported one research assistant during the first 21 months of the contract, and two or more (when funds allowed) research assistants during the subsequent period of the contract, until September 30, 1988. Carry-over funds supported one research assistant until December 31, 1988.

The total budget for this research program over its 9.25 year duration was $586,644.57, an amount which supported 2.33 person-years of full time equivalent effort by the Principal Investigator, and approximately 18.2 time equivalent person-years of research effort by graduate research assistants. The efforts of this research staff produced the eight archival journal papers listed in Appendix D, reprints of which are included in Appendix E of this report; the 31 oral or poster papers at IEEE and APS plasma meetings which are listed in Appendix F, and the abstracts of which are included in Appendix G of this report. In addition, the efforts of the ONR-supported research assistants in the UTK Plasma Science Laboratory produced four graduate

theses, the title page and abstracts of which are included in Appendix H. The ONR contract also supported a great many other activities, including participation on national boards and committees by the Principal Investigator, invited talks, and travel to and participation in overseas international meetings. Trip reports on these international meetings, travel to which was supported by ONR contract, were submitted to the Navy shortly after they took place. A text of these trip reports is included in Appendix J of this report. The activities of each year have been documented in detailed interim scientific reports, and/or in proposals, the UTK report number of which is listed in Table 1. These have been submitted to ONR and are available in its archives. In addition, each year of support required a proposal, which is documented by the UTK report numbers listed in the last column of Table I.

TABLE I

STATISTICAL SUMMARY OF RESEARCH PROGRAM

Year	Duration	P.I. Full Time Months	UGRA's GRA's, Half Time Months	Proposed yearly Budget	Proposal UTK Report Number	Interim UTK Report Number
1	1/1/80-12/31/80	3	6	$34,828.00	PSL 79-2	PSL 80-2
2	1/1/81-9/30/81	3	26	$35,000.00	PSL 80-2	PSL 82-1
3	10/1/81-9/30/82	3	27	$54,865.00	PSL 80-2	PSL 82-1
4	10/1/82-9/30/83	3	19	$59,198.00	PSL 82-1	PSL 83-2
5	10/1/83-9/30/84	3	33	$65,760.00	PSL 82-1	PSL 84-2
6	10/1/84-9/30/85	3	27	$69,658.00	PSL 84-2	PSL 87-4
7	10/1/85-9/30/86	3	24	$74,896.00	PSL 84-2	PSL 87-4
8	10/1/86-9/30/87	3	29.5	$81,505.57	PSL 84-2	PSL 87-4
9	10/1/87-9/30/88	3	25	$81,026.00	PSL 87-4	This Report
10	10/1/88-3/31/89	1	3	Carry-over Funds	---	This Report
Total	9.25 Years	28 Months 2.33 Person-Years	219.5 Months 9.15 Person-Years	$560,113		
	Returned to ONR			($3,376.43)		
	FY 1983-Equipment Grant			$29,908.00		
	Grand Total			$586,644.57		

Objectives of Research

Our goals during the initial two years were to set up, with ONR support, a modified Penning discharge (one operated in a magnetic mirror field) in the UTK Plasma Science Laboratory, and then to identify and confirm the existence of the geometric mean plasma oscillation in this plasma. These objectives were met by the end of the second year of the contract. Exploratory-research during the second year of the contract revealed broadband, white-noise-like RF emission from the modified Penning discharge, of a kind that might be useful for jamming or EMI simulation. Strong axial and radial electric fields also were observed, as well as high levels of plasma turbulence.

It became our objective during the third to fifth years of the contract to study the strength and nature of the broadband emissions from the classical Penning discharge; to study the interactions of microwave radiation with the modified Penning discharge plasma; to study the drift waves and turbulence observed in the plasma using time series analysis techniques; and to understand the anomalously high electrical resistivity observed in this plasma. Research on these topics revealed interesting phenomena, the study of which became the objective of our research in the last four years of the contract, until termination of this research program. One of these latter topics was the active modification of plasma turbulence by an effector probe, which allowed us to both enhance and damp the spectrum of plasma turbulence, and thus presumably to enhance or decrease the transport coefficients which depend on plasma turbulence. We also implemented a way to measure the effective collision frequency of the electrons as they scatter off

turbulent electric field fluctuations in the plasma, and to relate this to existing theories of turbulent scattering of electrons by plasmas, such as that by Galeev and Sagadeev. Finally, it became our objective also to apply mathematical methods developed to understand chaotic phenomena to plasma turbulence, using a newly available commercial software program for analysis of the data.

Nine-Year Technical Results

During the entire course of this 9.25-year research effort, the overall objective has been exploratory basic research on physical processes in a highly turbulent, steady-state modified Penning discharge plasma. Within this overall objective, the generosity of the Navy in supporting two graduate research assistants allowed us to pursue more than one research topic at a given time, to develop new diagnostic methods, and to pursue all the major research topics which we investigated to a resolution. Some topics on which we worked over this 9.25-year period led to new, interesting results which represented a first-time contribution of its kind; some topics added to our armamentarium of novel or unique diagnostic methods which contributed to Navy contract research, as well as to the overall research program of the UTK Plasma Science Laboratory; and a few research topics did not work out as we originally hoped for.

In approximate chronological order, the basic research topics covered during this 9.25-year period started with our initially proposed research on the geometric mean plasma emission process, a mode of plasma instability that was jointly discovered by the Principal Investigator and Prof. Igor Alexeff

of the University of Tennessee. The initial objective of this contract was to experimentally identify and confirm the existence of the geometric mean interpenetrating beam-plasma instability in a modified Penning discharge. This work occupied approximately the first 2-1/2 years of this contract. The scientific results were reported in ref. 1 of Appendix D, (a full length copy of the archival paper is in Appendix E), and in the conference presentations, the abstracts of which are listed as refs. 1, 2, and 4 of Appendix F. Abstracts of these papers are included in Appendix G, on pages G-1, G-2, and G-4.

The second major research topic was to further explore the radio frequency emissions from the steady state, electric field dominated plasma in the modified Penning discharge. These broad-band RF emissions are potentially of interest to the military for jamming and RF power generation applications. The results of this research were reported in the archival papers listed in Appendix D in Refs. 2 and 4, full length copies of which are included in Appendix E. In addition, this research on broadband RF emissions was reported in a series of conference papers which appeared over a four year period and are listed in Appendix F as refs. 3, 5, 7, 12, 13, and 18. Copies of the abstracts of these papers are included in Appendix G, on pages with the same numbers.

The next major research topic to attract our interest was the study of plasma fluctuations and turbulence in the modified Penning discharge. This discharge is highly turbulent, with a high level of anomalous plasma resistance. The results on self-generated plasma fluctuations and turbulence were published in archival form in ref. 6 of Appendix D, a full length copy of which is included in Appendix E of this report. This work on plasma

fluctuations and turbulence was also described in three conference papers listed as refs. 14, 15, and 28 of Appendix F, abstracts of which are included in Appendix G on pages with corresponding numbers.

The next topic investigated was characterization of the properties of these electric field dominated plasmas, in particular the high axial and radial electric fields, and the highly anomalous electrical conductivity which these strong electric fields implied. This work was described in archival form in Ref. 3 of Appendix D, a reprint of which is included in Appendix E, and it was also described in conference presentations which are listed as refs. 6, 8 to 11, and 27 of Appendix F. Abstracts of these conference presentations are included in Appendix G, on pages with corresponding numbers.

After characterizing the plasma parameters and the nature of the anomalous resistivity in this plasma, an attempt was made to actively modify the level of plasma turbulence by putting external signals on an "effector" probe located at the plasma edge. This work on active modification of plasma turbulence, which has continued until the end of this research effort, has been written up thus far in archival form in Ref. 7 of Appendix D, a copy of which is included in Appendix E. This work also appeared as conference presentations in Ref. 16 and 25 of Appendix F, abstracts of which are included in Appendix G, on pages with corresponding numbers.

Finally, another line of research which continued until the end of this contract is measurement of the effective collision frequency of the electrons in this plasma, as they scatter off the turbulent electric fields in this discharge. We developed a diagnostic method to measure the effective collision frequency through the half-width of the RF absorption peak of the electron cyclotron

resonance frequency, and we have shown that this effective collision frequency is up to a factor of 20 times higher than the binary collision frequency of electrons with neutral gas atoms, which is the dominant binary collision process in this plasma. These turbulent fluctuations are the source of the anomalous resistivity of this plasma which was described in earlier reports. Measurement of the effective electron collision frequency, and its relation to the theories of Galeev and Sagadeev have been described thus far in archival form in ref. 8 of Appendix D, a full length copy of which is included in Appendix E; and in conference presentations, which are listed as Refs. 20, 22, 23, and 26 of Appendix F, abstracts of which are included in Appendix G on pages with corresponding numbers.

The final scientific areas which have been supported by the Navy contract include a collaboration with Prof. Igor Alexeff in the field of geophysics, in which an MHD model of the earth's magnetic field was described in a conference presentation listed as ref. 19 of Appendix F; and an applied piece of work on plasma ion implantation which was written up for conference presentation as ref. 24 of Appendix F. Abstracts of these two miscellaneous pieces of work will be found in Appendix G, on pages with the corresponding numbers.

In addition to the scientific objectives and their outcomes described above, this Navy contract also served the secondary function of allowing the Principal Investigator to build up, at the University of Tennessee in Knoxville, the UTK Plasma Science Laboratory which, with additional support from the Air Force, and the Army Research Office, has become a Southeastern regional center of research in plasma science. Essentially the

entire first year of this 9.25-year contract period was necessary to set up the vacuum system, the magnet system, and the plasma diagnostic instruments required to do plasma-related research at the University of Tennessee, and to achieve our first plasma.

Among the diagnostic and supporting efforts funded by this contract were an extensive software development program which resulted in a master's thesis by Mr. Saeid Shariati, on Langmur probe data reduction, a computer program which allowed us to automatically accomplish Langmuir probe data reduction. This work was written up in ref. 29 of Appendix F, a conference presentation the abstract of which is included in Appendix G. In addition to the Langmuir probe data reduction, an extensive computer program to allow the analysis and correlation of plasma fluctuations for more than one probe was provided us by the University of Texas at Austin. This work was modified for our research program in a masters thesis by Mr. Reza Ghayspoor. An archival description of this data handling system is in ref. 5 of Appendix D, a full length reprint of which is in Appendix E. Two conference presentations on this subject are listed as refs. 17 and 21 of Appendix F, the abstracts of which are included in Appendix G.

In addition to the computer software development required for the two above diagnostic systems, we developed, for the first time anywhere, a method of measuring the effective collision frequency in a plasma, using the half-width of the resonance peak at the electron cyclotron resonance frequency. The implementation of this diagnostic method was written up in conference presentations listed as refs. 20, 22, 23, and 26 of Appendix F, the abstracts of which are included in Appendix G. on pages with corresponding numbers.

Results of Related Programs

This contract also supported other activities in aid of our experimental and theoretical research program. One such activity was the purchase of equipment, including low frequency and high frequency (microwave) network analyzers, with $233,745 of fiscal year 1985 funds which UTK was given by AFOSR under the Department of Defense-University Research Instrumentation Program (URIP). Another activity, in the third and fifth year of this contract, was participation by the Principal Investigator in the International Conferences on Plasma Physics, held during the early summers of 1982 and 1984, the first in Goteborg, Sweden, and the second in Lausanne, Switzerland. An archival paper describing research done under this ONR contract was presented at each meeting. An extensive trip report was submitted on each of those two years to ONR, which described technical developments at the conference, and the Principal Investigator's visits to European plasma-related laboratories before and after these conferences.

Finally, during the sixth through ninth years of this contract, it was used to partially support a pilot program, sponsored by AFOSR, to hire undergraduate students as research assistants affiliated with DoD contract research in the UTK Plasma Science Laboratory. Six students were hired under this pilot program during the first summer, of 1985. By 1988, the fourth year of the program, 34 students had participated in this program. The program was extremely successful in terms of furthering the research objectives of our contract, and introducing engineering students to ongoing experimental research programs in the plasma laboratory.

Utility of Results to the Navy

The steady-state electric-field-dominated classical Penning discharge may be a test bed to study physical processes that occur in intense microwave radiation and particle beam sources which are pulsed on time scales too short to allow ready investigation of their physics. The observation, during the second and third year of this contract, of broad-band, white-noise like RF emission over frequencies from 0.5 MHz to 2 GHz, was suggestive that this manifestation of the two interpenetrating beam instability might be useful for jamming communications, or for electromagnetic noise generation. Indeed, the emissions from the Penning discharge plasmas in the UTK Plasma Science Laboratory were capable, under the right conditions, of jamming both AM and FM radio reception in Ferris Hall, where the Electrical Engineering Department and the Plasma Lab are housed. Quantitative measurements undertaken in the third and fourth years of this contract indicated that the intensity of the RF emission was proportional to the electron number density rather than to the electron number density squared. This is characteristic of an incoherent radiation process in which each electron radiates power independently, rather than a collective, dipole-like emission in which intensity is proportional to the square of the number of electrons participating. Moreover, the overall efficiency of the emission process, defined as the integrated RF power divided by the dc input power to the classical Penning discharge, was less than about 0.1%, and had a functional dependence such that the emitted power decreased with increasing plasma density.

Other results of this research may be of utility to future Navy programs. The production and maintenance of steady state, high power density plasmas for such military objectives as weapons effects, high power lasers, and directed energy weapons may benefit from our observation and level of understanding of anomalous plasma resistivity due to plasma turbulence. During the fourth and fifth year of this experimental program, radial and axial profile measurements were made of the electrostatic potential, number density, and electron temperature of the modified Penning discharge. It was found that, under highly turbulent plasma conditions, axial electric fields, parallel to the magnetic field lines, were as high as several hundred volts per centimeter in this plasma. The implied electrical conductivities of these plasmas is anomalous, and is several hundred to several tens of thousands of times lower than the conductivity to be expected from binary collisional processes.

Another result of this research program is the diagnostic we developed to measure the effective collision frequency of the electrons in plasmas which are subject to strong fluctuating electric fields. We have confirmed the Galeev and Sagadeev theory for the effective plasma collision frequency, and demonstrated that their predicted scaling as well as their quantitative prediction agree with the effective collision frequency measured in our highly turbulent Penning discharge plasmas. This increased understanding of the effective electron collision frequency in plasmas should make it possible to predict with confidence the level and scaling of all plasma transport coefficients which depend on the electron collision frequency in turbulent plasma. In addition to this advance in theoretical understanding, this diagnostic method, or minor modifications of it, should be useful in Navy

applications such as shock tubes, ionospheric plasmas, etc., in which one wishes to measure the actual electron collision frequency, as opposed to estimating the electron collision frequency on the basis of tabulated cross sections for binary collisional processes.

Finally, our research of the last four years on the passive measurement of turbulent fluctuations in plasmas, and the active modification of the plasma turbulent spectrum, may have far reaching implications for Navy applications. Although these topics need to be researched more than was possible under the current contract, there are already very interesting indications that the application of chaos-related methods to plasma turbulence can reveal underlying uniformities and relationships which are not otherwise obvious in the apparently random nature of fluctuations of number density or plasma potential. By being one of the first research groups in the country to apply a commercially available software program which generates chaos-related parameters to plasma turbulence, we have shown the way to a promising method to shed light on the origin of plasma turbulence.

Our demonstration of active modification of the turbulent spectrum of potential fluctuations, with an external effector probe driven by a signal of known amplitude and frequency, also has many interesting implications for Navy-related applications. We have demonstrated the not unsurprising fact that enhancing the turbulent spectrum leads to heating of the plasma through energy cascading in the turbulent spectrum. Much more interesting, however, is our demonstration that driving the self-generated plasma turbulence spectrum with an external signal of low frequency can damp the turbulent spectrum. The reduction in the overall level of turbulence at

frequencies above a few tens of kilohertz was from 10 to 20 dB under some conditions, while other plasma parameters remained the same. This great reduction in the total level of turbulent energy in the plasma implies not only that the amplitude of turbulence should decrease, but also that the effective collision frequency due to turbulence, and all of the transport coefficients which depend on the presence of turbulence, should also be reduced. If this observation of ours on plasma turbulence could be carried over into the realm of ordinary fluid dynamics, it would then be possible for the Navy to contemplate reduction of the turbulent component of drag in aircraft or submarine motion.

THE UTK PLASMA SCIENCE LABORATORY

Scope of Research Programs

Course offerings and active research in the field of plasma science have been underway at the University of Tennessee, Knoxville, since 1970. The UTK Plasma Science Laboratory was set up in its present form in 1980, and occupies the entire first floor of Ferris Hall, the Electrical Engineering Department's building on the UTK campus. Using our ONR contract as a legal vehicle, the UTK Plasma Science Laboratory acquired in 1980 approximately $400,000 of plasma-related instrumentation from the NASA Lewis Research Center, which enabled us to begin a research program on electric field-dominated plasmas. This inventory of laboratory equipment has been supplemented over the last several years by used, but serviceable, surplus equipment obtained from Department of Defense installations within a half-day's driving distance of Knoxville.

The UTK Plasma Science Laboratory is equipped with a variety of operating plasma diagnostic instruments, and a large inventory of power supplies, electronic test equipment, and RF and communications-related electronic equipment and hardware which supported our exploratory research efforts. The UTK Plasma Science Laboratory also has two inexpensive-to-operate steady state Penning discharge plasmas on which instruments can be developed and debugged, and on which data of unusually high quality can be taken with our existing instruments. A grant of FY 1985 funds amounting to $233,743 from AFOSR under the DoD-University Research Instrumentation Program (URIP), has allowed us to purchase state-of-the-art RF network analyzers and other state-of-the-art electronic test equipment which not only

provides our students training with the latest equipment, but also allows us to take plasma diagnostic data of a quality and kind that is possible to very few other university-based research laboratories.

Since 1980, the UTK Plasma Science Laboratory has been partially supported on a continuing or occasional basis by contracts with Office of Naval Research, the Air Force Office of Scientific Research, the Army Research Office, the National Science Foundation, and the Tennessee Valley Authority. In calendar year 1988, he total budget of the UTK Plasma Lab was just under $300,000. The UTK Plasma Science Laboratory is affiliated with the Electrical and Computer Engineering Department of the University of Tennessee in Knoxville, and focusses its research efforts on steady-state, electric field-dominated plasmas. Our emphasis on steady state plasmas makes it much easier for us to take diagnostic data of high quality, and to vary parameters in an exploratory way to identify and study the physical processes which occur in these plasmas. The emphasis on electric field dominated plasmas (those plasmas having strong radial and/or axial electric fields penetrating them) has allowed us to focus on an area of plasma science which has been neglected both within the DoE's fusion program, and by other university research groups in the field of plasma science. Particular electric field dominated plasmas under study in the UTK Plasma Science Laboratory include Prof. Igor Alexeff's AFOSR contract on the Orbitron maser, which is of interest because of its capability to produce sub-millimeter microwave emission at power levels in excess of one watt; and plasmas generated by Penning discharges, which are highly turbulent, and provide a conventient test bed for research on plasma turbulence, anomalous electrical resistivity,

and the effective electron collision frequency resulting from turbulent, anomalous electrical resistivity, and the effective electron collision frequency resulting from turbulent, fluctuating electric fields within the plasma.

Laboratory Space and Utilities

The UTK Plasma Science Laboratory occupies approximately 1800 sq. ft. on the ground floor of Ferris Hall on the UTK campus. This floor also has offices available with six desks for research assistants associated with the Laboratory, and a loading dock for equipment. The Laboratory is furnished with running water, two sets of two inch supply and discharge mains at city water pressure for cooling of the magnetic field coils; city sewers; 70 KVA of 440 volt three-phase electrical power; 120 KVA of three-phase, 220 volt electrical power, fluorescent lighting, air condtioning, tile floors, and building services. In addition, the Plasma Science Laboratory has available approximately 400 sq. ft. of office and light-duty research space on the 5th floor of South Stadium Hall,under the nearby football stadium.

The Electrical Engineering Department offers further services and facilities, including a student machine shop, an electronic parts store, a technical services shop which can maintain and repair equipment, secretarial services, a photo-copy machine, a Xerox 8010 Star word processor with a laser printer, and a wide range of computational facilities.

The impact of the ONR contract on the UTK Plasma Science Laboratory can be seen by comparing Figure 1 with Figure 2 and 3 below. On Figure 1 is shown the UTK Plasma Science Laboratory in early 1981, during the early phases of ONR funding. The coils, which had been obtained with NSF funding about ten years earlier, are at the center of the floor. Figure 2 and 3 are recent

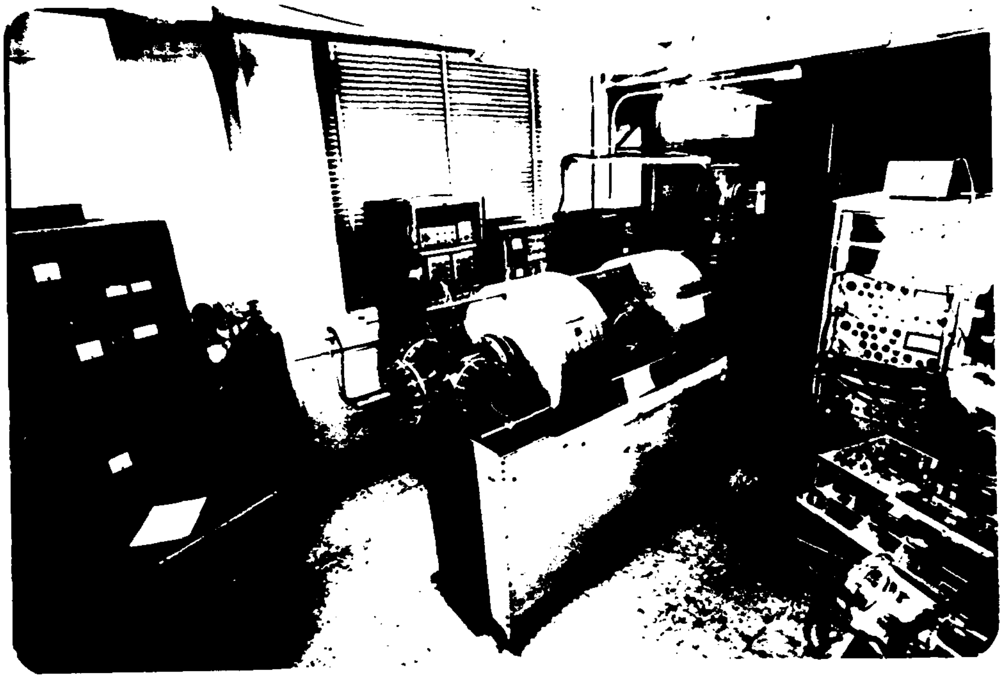


Figure 1

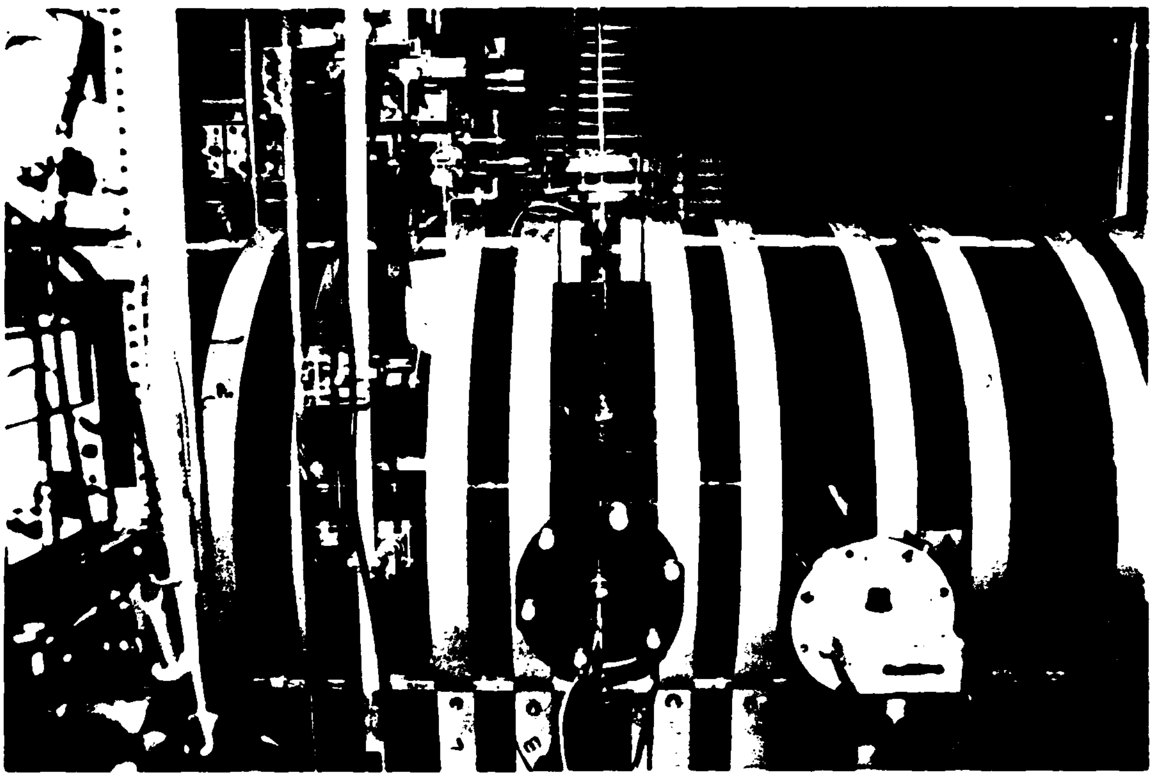


Figure 2

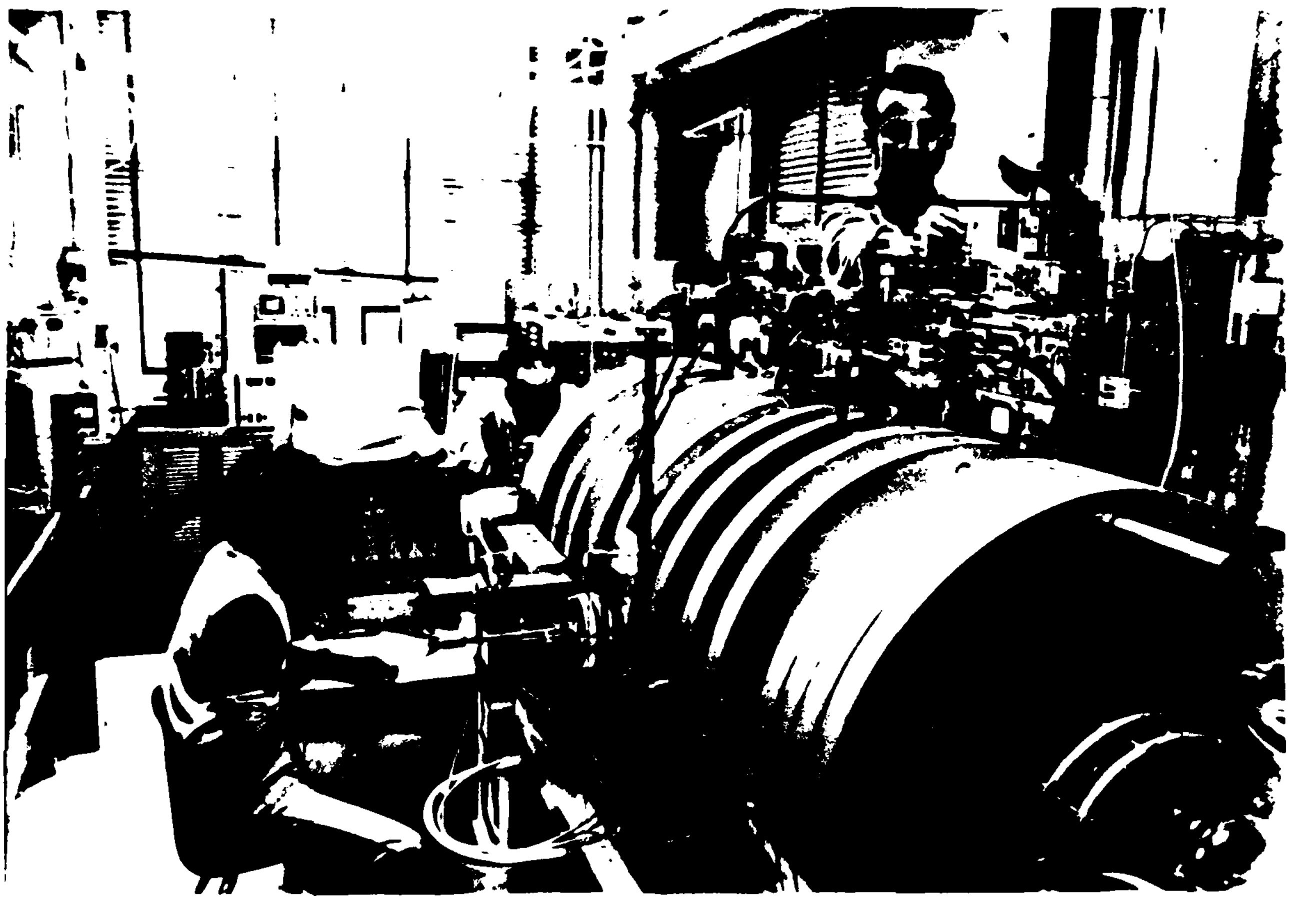


Figure 3
The ONR Experimental Apparatus at the
UTK Plasma Science Laboratory

photographs of the ONR equipment shown in Figure 1, with the HP network analyzer to the left of the coils, and several other diagnostic systems in place.

Impact of DoD-URIP Equipment Grant

In 1983 we submitted a proposal to the AFOSR for $233,743 to buy new, state-of-the-art equipment for our AFOSR research effort in the UTK Plasma Science Laboratory. Most of this money was to be spent on low-and high frequency network analyzers, to make possible highly sophisticated active and passive plasma diagnostics. In April, 1984, we were pleased to learn that this proposal was fully funded with fiscal year 1985 money. This money became available to us in January, 1985.

According to the Hewlett Packard representative, the network analyzers which we purchased represent the most sophisticated and highest-tech item in the Hewlett Packard equipment inventory. In order to operate this equipment, Prof. Rosenberg and one of the ONR graduate research assistants from the UTK Plasma Science Lab took a special course in Atlanta, Georgia, in August, 1985. The new instrumentation has greatly facilitated the measurement of RF emissions above 1 gigahertz, and makes possible quantitative measurements, which heretofore have been extremely difficult, at frequencies up to 18 GHz.

The Hewlett-Packard network analyzers have played a central role in the ONR research program since they became available in late 1985. Our HP model 8510 microwave network analyzer has been used to measure the absorption of microwave radiation at the electron cyclotron resonance frequency, information which allows us to determine experimentally the

effective collision frequency in our plasma. The low frequency network analyzer has also been useful in measuring the power spectrum of electrostatic potential fluctuations and electron number density fluctuations in our plasma, data which are necessary for experimental comparison with the Galeev-Sagadeev theory for the effective collision frequency due to fluctuating electric fields in a plasma. The 80 dB dynamic range and absolute calibration of these instruments have made them particularly useful in our research.

Specalized Research Equipment Used on This Contract

Over the past nine years, the UTK Plasma Science Laboratory has built up an inventory of specialized research equipment, plasma diagnostic instrumentation, and computerized data reduction capabilities that are, if not unique, at least well above average by university standards. Among the specialized equipment at the UTK Plasma Science Laboratory available for our research program are the following:

1. A 20 centimeter inside bore, 0.35 tesla, 18-coil, water-cooled solenoid complete with power supply, cooling water, and a control system capable of providing steady state magnetic fields for plasma research. This facility is currently dedicated to the ONR Research Program.
2. A 17 centimeter inside diameter, 0.50 tesla, 8 coil water-cooled solenoid, with power supply, cooling water, and control system. This facility is used in the current AFOSR research contract for the classical Penning discharge, and is capable of providing a steady state magnetic field for plasma research.
3. Both of the above mentioned magnet systems are furnished with glass vacuum systems, which allow flexibility in rearranging diagnostic probes and sensors. The glass vacuum systems also allow electrostatic potential

fluctuations and RF emissions from the plasma to be detected outside the vacuum system. Each of these vacuum systems has a refrigerated cold trap, using a special freon which achieves -130 °C, and each system can reach base pressures in the mid or low 10^{-6} torr range. Each vacuum system also has a turbo-molecular vacuum pump which reduces the background contamination which would otherwise occur from diffusion pump oil. These vacuum systems have been in operation for several years, are throughly debugged, and are extremely reliable research tools.

4. The UTK Plasma Science Laboratory has available a 40 kilovolt, 1 amp dc high voltage power supply which is used to energize the Penning discharges on the current AFOSR and ONR experiments. This power supply has safety interlocks, overcurrent and overvoltage trip protection, and allows the output voltage to be varied from a few hundred volts to a maximum value of 40 kilovolts, while drawing up to 1 amp of current. This power supply uses vacuum tube electronics, and therefore operates reliably in spite of the occasional arcs characteristic of steady state Penning discharge plasmas.

5. A major recent addition to our inventory of specialized research equipment is a Hewlett-Packard model 8510 high frequency network analyzer which is capable of operating from 45 MHz to 18 GHz. This network analyzer is shown in Figure 4, and was purchased with part of the DoD-University Research Instrumentation Program grant awarded to the UTK Plasma Science Laboratory. This analyzer allows us to measure the frequency response and impedance function of microwave equipment over the frequency range of the instrument. It facilitates absolute measurements of RF power, and turbulence measurements over a dynamic range of 80 dB. Very few other

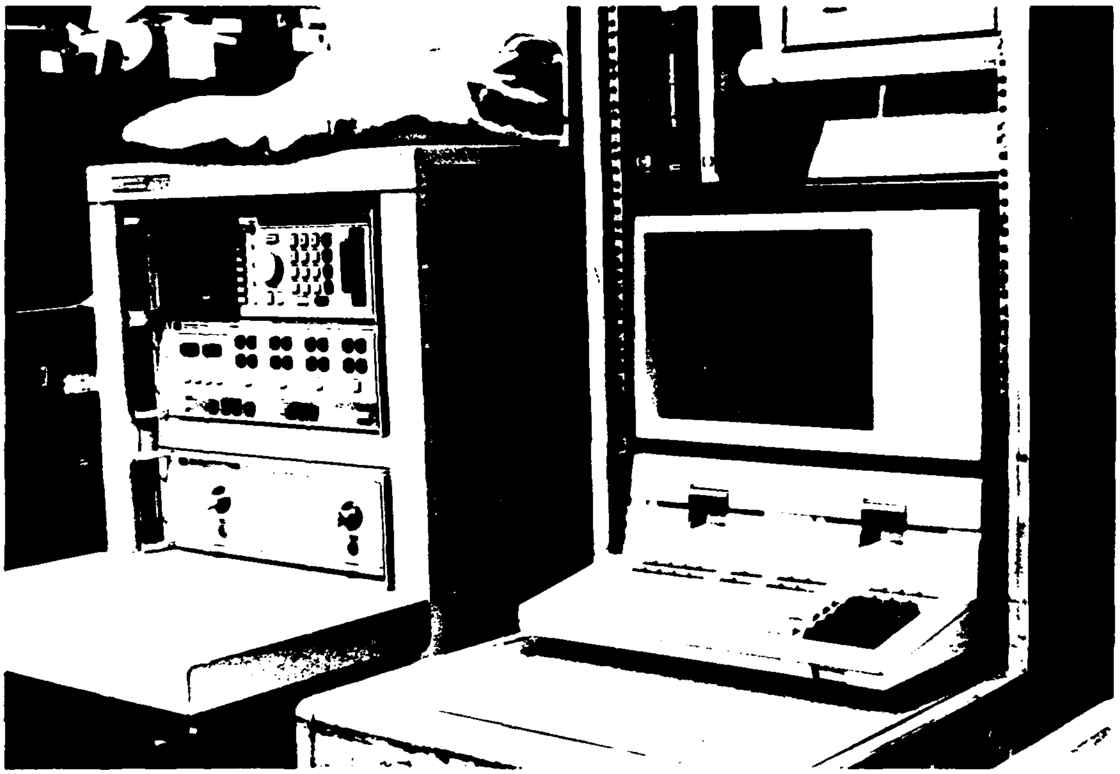


Figure 4

university-based plasma research laboratories in the country possesses such an instrument.

6 As part of the instrumentation purchased with the AFOSR-DoD-University Research Instrumentation Program grant, we also bought a Hewlett Packard model 3577 low frequency network analyzer, the frequency response of which ranges from 5 Hz to 200 MHz. This network analyzer can be used for calibration of absolute signal levels, and for measuring the frequency response of our diagnostic equipment. It too, has a dynamic range of 80dB.

Plasma Diagnostic Instrumentation

During the past nine years, the UTK Plasma Science Laboratory has built up an inventory of plasma diagnostic instrumentation which makes it well-equipped by university standards. Some of this instrumentation is the first of its kind and has been documented in the literature. Some of these publications are listed in Appendix F. The most notable items of our diagnostic instrumentation are the following:

1. Vacuum Mass Spectrometer - The vacuum system used for the classical Penning discharge is equipped with a vacuum mass spectrometer which not only allows us to detect leaks in the vacuum system, but also confirms that the gas in the vacuum system during an experiment is that intended.

2. Capacitive Probes - We have developed a dual channel capacitive probe system complete with cables, amplifiers, filters and shields. The entire system has a frequency response which is virtually flat from 1 kilohertz to 10 megahertz. These probes can be positioned at various locations immediately outside the glass vacuum system, where they can detect the electrostatic potential fluctuations associated with plasma instabilities and turbulence.

Under other conditions of operation, capacitive probes are inserted into the vacuum system, and are positioned in the vicinity of the plasma boundary.

3. Langmuir Probes - The UTK Plasma Science Laboratory has a number of Langmuir probes and a high voltage Langmuir probe power supply system which is used for measuring plasma parameters. An unusual problem encountered in these electric field dominated plasmas is that the plasma potential is often quite high, on the order of kilovolts. For this reason, it is necessary to bias the Langmuir probe to several kilovolts in order to take a Langmuir probe curve which will allow us to measure the electron kinetic temperature and number density. We have developed a data handling system which will take the Langmuir probe traces automatically, and print out, on line, the plasma parameters based on the Langmuir probe trace. This software development is described in the next section.

4. Retarding Potential Energy Analyzers - The vacuum system used for the classical Penning discharge has a retarding potential energy analyzer permanently installed. When data are taken, this analyzer is energized by an external power supply on an equipment rack. The retarding potential energy analyzer is used to measure the integrated energy distribution function of ions lost along the axis of the magnetic field in the two Penning discharges.

5. A Polarization Diplexing Microwave Interferometer - This instrument was developed in collaboration with Prof. Andrew L. Gardner of Brigham Young University. This instrument can use both modes of polarization of the microwave radiation at 28 GHz, and can detect densities as low as 10^8 electrons per cubic centimeter.

6. Analog-to-Digital Data Handling System - The UTK Plasma Science Laboratory has an analog-to-digital data handling system based on three LcCroy Model 8837, 32 megahertz transient recorders interfaced to an IBM AT computer. This system is capable of taking three simultaneous channels of data, and digitizing them at rates up to 32 MHz. This digitized data can be displayed on the screen of the IBM AT computer, and then sent by a hard-wire data link to the Electrical Engineering Department's VAX 780-11 computer for analysis by approxpriate software programs, or analyzed on-line by the AT computer.

7. Calibrated, Broadband Antennas - As part of our on-going research program to measure RF plasma emissions, we have developed two calibrated, broadband antennae, which have a very broad and flat frequency response, from approximately 100 MHz to GHz. In addition, they have been absolutely calibrated to measure the incident power, in watts, received from our plasmas. The instrumentation and hardware necessary to make and implement these absolute calibrations have also been developed, and include the HP 3577 low frequency network analyzer, described in the previous section.

8. Other Research Equipment - In addition to the above individual items of plasma diagnostic equipment, the UTK Plasma Science Laboratory is well equipped with a variety of power supplies, RF voltmeters, signal generators, microwave hardware and accessories, and other equipment necessary to do RF detection and plasma research. Over the years, we have built up our inventory of research equipment through the DoD Surplus Property Utilization Program, which makes available used but serviceable equipment

to DoD contractors. This has allowed us to obtain euqipmnt for exploratory research which we could not afford otherwise.

<u>Specalized Data Reduction Capabilities</u>

At the UTK Plasma Science Laboratory, we have attempted to stay at the leading edge of the development of plasma diagnostic software and digital data handling and reduction methods. The resources of our Electrical and Computer Engineering Department are very valuable in this respect. Some of the hardware and software which we employ are as follows:

1. <u>The VAX 780-11 Computer</u> - This computer is installed in Ferris Hall, and is readily available to users in the Electrical Engineering Department. There are four hardwired data links from the VAX computer to the UTK Plasma Science Laboratory, three of which are presently connected to terminals and/or the minicomputers described below. This computer makes available on-line data reduction of fairly sophisticated programs, the running of which on our minicomputers in the Plasma Lab would either take too long, or not be possible.

2. <u>A HP 9836 Series 200 Minicomputer</u> - The primary function of this unit is to run the HP 3577 and HP 8510 network analyzers in their fully automated mode. It can also be used as a stand-alone computer for other data handling and data processing tasks. This computer is connected by a hardwired link to the EE Department's VAX 780-11 mainframe computer.

3. <u>A LeCroy 3500 SA Minicomputer</u> - This LeCroy Minicomputer was used as a three channel, 32 MHz transient recorder and digitizer system with three LeCroy model 8837 transient recorders. In addition, the LeCroy system also has a four channel, 1 MHz model 8501 analog-to-digital converter which was

used at lower frequencies, when the system was used as a smart X-Y plotter or oscilloscope. The LeCroy 3500 SA minicomputer was connected by a hardwired data link to the EE Department's VAX 780-11 mainframe computer, and could transmit digitized data to that computer for analysis by various software programs. After about 5 years of use in our research program, this unit was retired from service in late 1988 because of its limited capabilities when compared to the IBM AT system described below.

4. An IBM-AT Minicomputer Based Data Handling and Reduction System - In early 1987, an IBM-AT computer complete with an extensive software library and a color printer became available to UTK Plasma Science Laboratory through our AFOSR research contract. In order to take advantage of the on-line data reduction capabilities which this AT computer made possible, we purchased, with ONR funds, an interface which allowed us to use our LeCroy Model 8837 transient recorders and the LeCroy Model 8501 low frequency transient recorders with the AT computer. This arrangement allowed us to take data from capacitive probes or other transient signals related to plasma parameters, digitize them, and put them directly on analysis programs built into the IBM AT computer. This made it possible to reduce, for example, our fluctuating potential data using the methods of chaos dynamics on the AT computer, without requiring the ECE Department's mainframe VAX 780-11 mainframe computer. The new LeCroy-AT transient recording, data handling, and data reduction system allowed a great deal more flexibility than the previous arrangement with the LeCroy 3500 computer, including on-line data reduction and much shorter data turnaround times.

5. Dynamical Systems, Inc. Nonlinear Dynamics Software Program - In order to apply recently developed advances in chaos theory and nonlinear dynamics to our plasma fluctuation data, we obtained a commercially available software program from Dynamical Systems, Inc. of Tucson, Arizona. This program is capable of taking a time series from a fluctuating quantity, such as the electrostatic potential fluctuations at the edge of a plasma, or the number density fluctuations within a plasma. The software package contains routines which plot in two or three dimensions, calculate Fourier spectra, reconstruct phase portraits, take Poincare sections, compute correlation dimensions, compute Lyapunov exponents, and perform various other data manipulations. This Dynamical Systems software program has allowed us, with a minimum investment of time in software development, to apply the powerful methods of nonlinear dynamics and chaos theory to the problem of understanding plasma turbulence and fluctuations in our Penning discharge plasmas.

6. Software for Plasma Turbulence Analysis - The software required to analyze the statistical properties of simultaneously sampled signals is based on a time series analysis computer program very generously furnished to us by Prof. E. J. Powers of the University of Texas, Austin. This program has been modified for use on the EE Department's VAX 780-11 mainframe computer. This program has the capability of displaying such statistical properties of the plasma fluctuations as the auto and cross power spectra of two simultaneously sampled channels, phase spectra of the fluctuations between two channels, the coherence spectra, and finally it also contains the output software package required to plot the calculated data.

7. Computerized Reduction of Langmuir Probe and Retarding Potential Energy Analyzer Data - The LeCroy model 8501 transient recorder system has been modified to interface with the IBM AT Computer, and act as a smart X-Y plotter, to do real time, on-line data reduction from such diagnostic instruments as Langmuir probes, retarding potential energy analyzers, capacitive probes,and charge exchange neutral energy analyzers. The software required to support this and similar plasma diagnostic data reduction systems was not available from LeCroy or any other manufacturer. Mr. Saeid Shariati, a former graduate student in the Department of Electrical Engineering (who now works for the General Electric aircraft engine plant in Cincinatti, Ohio), has, for his master's thesis, developed software for the LeCroy 3500 transient recorder system which reduces data from a retarding potential energy anayzer and the high voltage Langmuir probe system, as well as our charge-exchange neutral energy analyzer system. This software is now in the process of being modified for the IBM AT computer.

Weekly Plasma Seminar

An important part of our research activities at the UTK Plasma Science Laboratory is a weekly Plasma Seminar in which the senior faculty and all research assistants participate, along with undergraduate students and any one else who is interested. Our graduate research assistants are expected to give at least one hour-long seminar on their work during each semester. In addition, we obtain outside speakers from the Oak Ridge National Laboratory or visitors to the campus to supplement our seminar schedule. The nature of this weekly seminar can best be appreciated by looking over some of the topics which were covered in the academic years covered by this contract. Copies of

our seminar schedule are included in Appendix C of this report.

RESULTS OF EXPERIMENTAL RESEARCH PROGRAM

This research program was initiated on January 1, 1980, and spanned a total of 9.25 years. It was supported by two Office of Naval Research contracts, ONR-N00014-88-K-0174, and by its predecessor contract, ONR-N00014-80-C-0063. The ONR program manager for this work was Dr. Charles W. Roberson of the Office of Naval Research. In January, 1980, this research program was a new start at the University of Tennessee, Knoxville, and has remained the keystone of our efforts at the UTK Plasma Science Laboratory to establish and maintain a southeastern regional center for basic and applied plasma research. Our ONR contracts have allowed us to conduct research on electric field dominated plasmas, and to investigate the physical processes associated with RF emission, plasma heating, and turbulence in these plasmas.

Objectives of Research Program

The objectives of this research program were as follows:

1. To operate for experimental investigation a steady-state modified Penning discharge, which creates an electric field dominated plasma in a magnetic mirror field. Such a plasma is penetrated by strong radial and axial electric fields.

2. To optimize the operation of this Penning discharge to produce phenomena of interest, including radio frequency emissions at the geometric mean emission frequency and other frequencies; anomalous plasma resistivity; and plasma heating by the application of raw DC electrical power.

3. To determine the most effective electrode geometry, axial magnetic field profile, and plasma operating conditions which produce the phenomena of interest.

4. To develop flexible plasma diagnostic instruments and computer software programs to measure the phenomena of interest, where such instruments or software are not already in the inventory of the UTK Plasma Science Laboratory, or available commercially.

5. To measure the parallel and perpendicular plasma resistivity; determine whether this resistivity is anomalous, or due to well understood binary collisional processes; and to compare the measured resistivity values with theoretical predictions.

6. To conduct exploratory studies of RF emissions over the widest possible frequency range, to determine whether any unanticipated phenomena or new modes of plasma instability are present.

7. To conduct theoretical studies of beam-plasma interactions, in order to provide insight into phenomena observed in the laboratory.

8. To develop a novel plasma diagnostic method, based on the full width at half maximum of the electron cyclotron resonance absorption peak, to measure the effective electron collision frequency in the plasma.

9. To compare the effective electron collision frequency measured with our new ECRH diagnostic technique, with available theories for the effective collison frequency duė to turbulent electric fields in a plasma, such as that by Galeev and Sagadeev.

10. To use recently developed methods of nonlinear dynamics, including chaos theory, to analyze and shed light on the physics of plasma fluctuations and turbulence.

The above research objectives are in rough chronological order, and represent the changing focus of our research program as it evolved over the 9.25 year period covered by this report. The generosity of ONR in funding two GRA's allowed us to pursue more than one of these objectives simultaneously. It was not uncommon for two or more of the scientific objectives to be pursued in parallel, while at the same time new plasma diagnostic methods were being developed. The long period over which ONR supported our work allowed us to pursue nearly all of these objectives to a resolution and/or final publication. During this nine year period, eight archival scientific papers were published, and thirty-one oral or poster papers were presented, most at the annual APS and IEEE plasma meetings. The ONR research program also supported four graduate theses, approximately twenty person-years of GRA research and training, and other scientific research and training activities detailed elsewhere in this report.

Accomplishments of The C.Y. 1980 Research Program

Experimental Research

By the end of May, 1980, the NASA equipment had been unpacked, documented, and organized on specially constructed shelves in the UTK Plasma Science Laboratory. During the month of February, a solenoidal magnet facility with a 40 kilowatt power supply and 20 cm diameter access bore was reconditioned and placed into operation. This magnet facility had an approximately 5:1 mirror ratio when operated in a magnetic mirror configuration, and the maximum magnetic field attainable with the existing power supply is $B_{max} = 0.4$ Tesla. The water-cooled coils were outfitted with safety interlocks which will not allow it to be operated unless cooling water is flowing. The entire system was put in working order and checked out, and it operates reliably. The glass vacuum system was assembled and made leak tight by early July, and was the pacing item in producing the first plasma in the apparatus. A 40 kilovolt, 1 amp dc power suply from NASA was assembled, debugged, and calibrated.

The diagnostic equipment required to make quantitative measurements of the plasma parameters were put into operation. These instruments included vacuum gauges, both ion gauges and thermocouple gauges for measuring the total background pressure of the vacuum system; and a monopole mass spectrometer, which monitors the composition of background gas in the vacuum system. These instruments indicate that the base pressure of the vacuum system is about 5×10^{-6} torr, and that the residual gas in the system is primarily water vapor, a consequence of the absence of a liquid

nitrogen cold trap on the system. Other instruments include a range of RF spectrum analyzers and signal generators capable of monitoring radio frequency emissions from a few kilohertz up to more than one gigahertz. The antennae, probes and waveguides required for these measurements were developed and put into operation. The polarization diplexing microwave interferometer was re-assembled, checked out, and minor shipping damage repaired. It allows us to measure the number density of the plasma by measuring the phase change between the ordinary and extraordinary modes of propagation in the plasma. This diplexing arrangement nulls out the effects of mechanical vibrations and thermal expansion, since these affect both modes of polarization equally. The remaining diagnostic which we put into service before starting a systematic program of quantitative measurements is a specialized Langmuir probe circuit, developed at NASA-Lewis, which allows Langmuir probe curves to be run in plasmas with floating potentials which may reach kilovolt levels.

Our efforts reached the point where we produced our "first plasma" on Friday July 11, 1980. A photograph of the plasma is presented in Figure 5. We reached this milestone essentially on the schedule laid down 6 months previously at the start of this contract.

Examination of the RF emission from the plasma with broadband spectrum analyzers revealed a rich variety of emission peaks between frequencies of 10 megahertz and 1 gigahertz. Under certain conditions of operation, broadband emission over this entire region of the spectrum was observed. The most prominent of the emission peaks was of a frequency, and functional dependence on plasma parameters, expected of the geometric mean

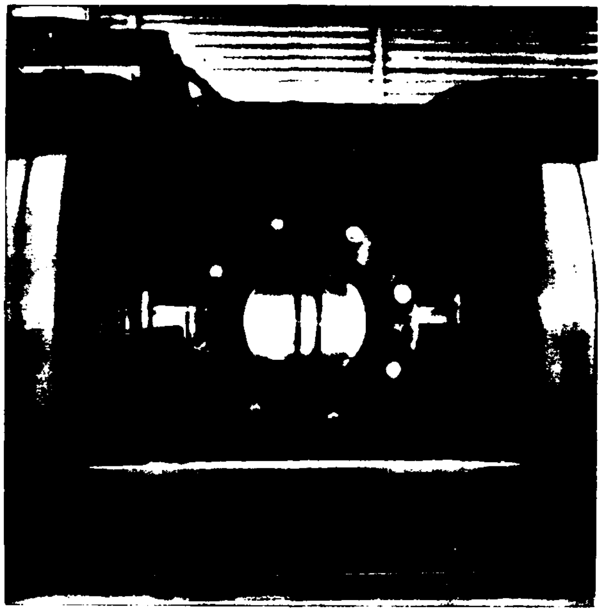


Figure 5

emission frequency. After an initial period of occasional arcing and plasma-wall interaction, the plasma is quite stable, and can be maintained in the steady state for hours. This steady state characteristic was extremely useful in later investigations of RF emission. Such emission surveys often are out of the question in pulsed experiments, because of the relatively long integration time required by spectrum analyzers to produce an adequate signal-to-noise ratio.

We proceeded in an orderly way to bring the diagnostics on line one by one as they were assembled, debugged, and documented. The polarization diplexing microwave interferometer allowed us to measure, at 26.8 gigahertz, the integrated electron number density across the diameter of the plasma. The central anode and the cathodes of the modified Penning discharge were water cooled in these and later experiments, and input powers of several kilowatts could be supported before additional cooling provisions are required. The plasma was operated in the steady state on July 11 at power levels up to 200 watts, and shortly after that time reached power levels of 1 kilowatt. The plasma is 12 centimeters in diameter at the midplane, and necks down to a diameter of about 5 centimeters at the mirror throats.

It has been extremely gratifying to observe the theoretically predicted RF emissions near the geometric mean plasma frequency in the modified Penning discharge. The original observations of this emission frequency were made on the NASA-Lewis Electric Field Bumpy Torus plasma (EFBT). There existed a possibility that the emission mechanism from that plasma had not been correctly identified, and would not be observable in the modified Penning discharge plasma.

By the end of calendar year 1980 we had a complete set of publishable quantitative measurements designed to test the theoretically predicted dependence of the emission frequency on ion mass, given by

$$\omega = \frac{\sqrt{\omega_{pi}\,\omega_{pe}}}{(2)^{1/2}(3)^{1/4}} \tag{1}$$

In the NASA-Lewis work, the possible dependence of the emission frequency on the ion mass was not suspected, in the complete absence of a theory.

Theoretical Research

Considerably more theoretical research relating to the geometric mean plasma emission was accomplished during calendar year 1980 than was contemplated in the original proposal. Many of the advances in theoretical understanding of the geometric mean emission process were made by Prof. Igor Alexeff of the UTK Electrical and Computer Engineering faculty, whose work in this area has been supported by the National Science Foundation, and not by the ONR. Prof. J. Douglas Birdwell of the Electrical and Computer Engineering Department has ably assisted us with numerical computations of the dispersion relations appropriate for the finite ion temperature regime.

The original paper published in Physical Review Letters, which described the discovery of the geometric mean plasma emission, contained a theoretical analysis based on a model in which two interpenetrating and counterstreaming beams of energetic electrons interacted in a background of cold ions. The dispersion function for this process consists of three terms; one term for each of the electron beams travelling in opposite directions, and a

third term representing the presence of cold background ions. In extending this theory, our first step was to consider the effect of finite ion temperature on the frequency and growth rate of the geometric mean emission process. This theory involved the replacement of the cold ion term of the dispersion relation with an integral representing the Fried-Conte function. The dispersion function for the interpenetrating electron beam case for finite ion temperatures therefore requires a computer solution, the parameter of which was the ratio of the ion thermal velocity to the electron beam velocity. The outcome of this theoretical analysis is described in a journal article which is included in Appendix E of this report. To summarize, it was found that neither the frequency nor the existence of growing (and therefore emitting) waves was affected in any important way by finite ion temperature, until the ion thermal velocity became comparable to the electron beam velocity.

Our original paper in Physical Review Letters reporting this discovery did not consider the effective conductivity which would be associated with the beam-plasma interaction that gives rise to the geometric mean emission frequency. It seemed intuitively possible to us that the collision of two interpenetrating electron beams in a background plasma would lead to much higher effective resistivities,and therefore lower conductivities, than the Buneman process or the travelling wave tube beam-plasma interaction, in which an electron beam interacts with a background plasma. The interaction of two interpenetrating electron beams with each other, should plausibly lead to a higher level of electrostatic turbulence, faster randomization of the electron beam velocity, and higher effective resistivities than the interaction of a single electron beam with a plasma.

A derivation was formulated which enabled us to calculate the expected effective conductivity in the plasma resulting from the interpenetration of two electron beams. We have termed this "effective" conductivity because the concept of conductivity must be used with great care in a physical situation in which equal and opposite electron beams interpenetrate in a plasma so that there are no net currents. The effective conductivity is then a measure of the rapidity or strength of the randomization of the electron beam, and is not the proportionality constant which appears in Ohm's law. A derivation of the effective conductivity is given in the Physics of Fluids article in Appendix E, and predicts a conductivity as follows:

$$\sigma_{GM} = 2.86\,\varepsilon_o\,\omega_{pe}\ \text{Siemens} \tag{2}$$

This is to be compared with the classical conductivity from a single beam-plasma interaction, for which the conductivity is given by

$$\sigma_B = 2\,\varepsilon_o\,\omega_{pe}\left(\frac{M}{m}\right)^{2/3}.\ \text{Siemens} \tag{3}$$

Thus, for deuterium gas, the resistivity due to the two interpenetrating electron beam case is 166 times larger than that to be expected from the Buneman beam-plasma interaction. Until now, the Buneman, or "anomalous" resistivity has been the highest known parallel resistivity possible to a plasma. The expression for the conductivity given by Eq. 2 above needs to be checked out experimentally.

Publications

During calendar year 1980, four publications were published with ackowledgement of support by the Office of Naval Research under this program. Two of were are papers at the 1980 IEEE International Conference on Plasma Science, which was held May 19-21 in Madison, Wisconsin. Copies of the two extended abstracts included in Appendix G, as G-1 and G-2, and each has acknowledgement of support by ONR. In one of these abstracts (G-2) I report on the effective resistivity in the electric field bumpy torus plasma at the NASA-Lewis Research Center. In the second abstract (G-1), my co-authors and I discuss the extension of our work in the Physical Review Letters to include a quantitative estimate of the effective conductivity due to the two-beam interaction process, and we also reported some initial results on finite ion temperatures. A third paper (G-3) entitled "RF Emissions From Beam-Plasma Interactions in a Modified Penning Discharge" was prepared for presentation at the APS Plasma Physics Division meeting in San Diego, California, from November 10-14, 1980. This paper was supported exclusively by the ONR contract, and reports the first quantitative data taken from the electric field dominated modified Penning discharge plasma at the UTK Plasma Science Laboratory.

A major paper (E-1) was published in the Physics of Fluids, which describes the theory of the geometric mean plasma emission; derives the real frequency and growth rate for the two interpenetrating beam-plasma interaction process; presents a derivation of the effective conductivity associated with this process; and discusses finite ion temperature effects. My

contributions to this paper have been supplemented by the theoretical efforts of Prof. Igor Alexeff and J. Douglas Birdwell, both of the UTK Electrical Engineering Department. A reprint of this paper is included in Appendix E (paper E-1) at the end of this report.

Accomplishments of the CY 1981-FY 1982 Research Program

Apparatus Modification and Operation

During this period of time, the experimental apparatus was under vacuum for at least two thirds of the total time, and the magnets, plasma, and diagnostic instruments were operated for at least several hundred hours, a high level of activity in an academic context. Much of the operating time was devoted to testing and debugging the diagnostic instrumentation which was put into service during this period, including the retarding potential energy analyzer, the high voltage Langmuir probe system, and the visible spectrometer. Perhaps 100 hours of actual operating time were devoted to taking publishable experimental data and/or exploratory investigations and measurements.

Because of the heavy usage of our magnet, the DC power supply for the coils (an old welding generator) twice required major repairs. As a result, we lost about 5 weeks. The high voltage DC power supply, water cooling system, vacuum system, and diagnostic instruments have, after initial debugging, operated with a high degree of reliability.

A major improvement in the facility accomplished during this period was to reduce the base pressure in the vacuum system,and consequently the level of impurities in the plasma during operation. Liquid nitrogen for the

vacuum system cold trap was available only with difficulty and at great expense in our laboratory, to such an extent that its routine use was infeasible. With a water cooled (cold) baffle in the vacuum system, the base pressure ranged from about 4 x 10^{-6} Torr to 10^{-5} torr, depending on the recent history of the vacuum system. At least two possible measures were available to us to improve the base pressure. One was to replace the oil diffusion pump with a turbomolecular pump, which does not present a problem of oil backstreaming into the vacuum system; and the second approach was to cool the baffle with a refrigerator. When the proposal for the current contract was initially submitted, it was intended to reduce the base pressure by using a turbomolecular pump. After this contract period started, however, a proposal to the Air Force Office of Scientific Research for another experiment and experimental apparatus was approved. It was our intention from the very beginning to use a turbomolecular pump for the Air Force apparatus. Therefore, it appeared to be the best strategy to buy and operate a turbomolecular pump on the Air Force apparatus first, before spending money for such a pump on the ONR contract. We then, with the approval of ONR, used the money originally set aside in the budget for the purchase of a turbomolecular pump, to purchase a closed cycle refrigerator to chill the existing cold trap on the ONR apparatus. This unit was delivered in June 1981, and was placed into service in Spetember 1981. It had the desired effect of significantly reducing the background pressure, to the point where the base pressure is now routinely in the range of 1 to 3 x 10^{-6} Torr. Our mass spectrometer indicates that at cold trap exit temperatures of -130°C, the dominant background impurity in the vacuum system (when the plasma is not

on) is water vapor. The modifications to the vacuum system required to install this cold trap took approximately 6 weeks during August - September 1981.

The antennas, probes, spectrum analyzers and other equipment needed for RF detection and measurement, which were placed into service immediately prior to the beginning of this time period, were further refined and tested, and routinely provided means to detect electrostatic potential fluctuations and near-field RF emissions in the vicinity of the experimental apparatus.

A retarding potential energy analyzer for the measurement of axial ion energy spectra from the plasma, which had been developed at NASA Lewis Research Center, was installed in the apparatus, and the necessary high voltage power supplies, xy plotter, and slow ramping circuit were fabricated and/or debugged. This unit presented unique problems, since it was desired to measure ion energies up to 10 keV, and this required special techniques to prevent high voltage breakdown both in the equipment rack and in the vacuum system. This retarding potential energy analyzer went into service in June 1981, and has since provided reliable data on the integrated ion energy distribution functions of the plasma.

Another major diagnostic instrument placed into service during this contract period was a Langmuir probe system. This unit is capable of operating at potentials up to 6 kilovolts above ground. These high potentials are required, since the modified Penning discharge plasma floats at high potentials during normal operation. We used Langmuir probes which were developed at the NASA Lewis Research Center, and a high voltage circuit

which allowed these probes to be operated at high floating potentials, while keeping the xy plotter needed to record the Langmuir probe trace near ground potential. This unit was debugged, assembled, and put into service in July 1981. This unit provided reliable data on electron number density, electron kinetic temperatures, and in a few instances, ion kinetic temperatures ever since. The Langmuir probe traces produced by this plasma are unusual not only in the high floating potentials which they assume, but in having an ion kinetic temperature several orders of magnitude larger than the electron temperature. In a particular run used as an example in our plasma diagnostics course, the ion kinetic temperature was about 1800 electron volts, under conditions for which the electron kinetic temperature was only 4 electron volts.

Studies of the Geometric Mean Emission Process

A major paper on the geometric mean emission mechanism, covering both its theoretical and experimental aspects, was published inthe Physics of Fluids. A copy of this publication is included in Appendix E, on pages E1-10. The theoretical results presented in that paper are in some cases not yet confirmed experimentally. It is these points that have been the focus of our experimental effort on the geometric mean emission process.

As noted in the reprint just mentioned, the geometric mean plasma frequency arises when two interpenetrating beams of electrons interact with a background of relatively cold ions. The frequency of this emission is predicted theoretically to be

$$\omega = \frac{\sqrt{\omega_{pe}\,\omega_{pi}}}{\sqrt{2}\,\sqrt{3}} = 0.537\,\omega_{pe}\left(\frac{M_e}{M_i}\right)^{1/4} . \tag{4}$$

We have observed radio frequency emissions, in the vicinity of the geometric mean plasma frequency, from the electric field dominated plasma generated in our modified Penning discharge. The expression in Equation 4 above has been found to be in agreement with emissions from the Lewis Electric Field Bumpy Torus Plasma. The predicted dependence on the ion mass was not previously tested experimentally, and this was the main thrust of the quantitative observations made during the first part of the current contract period.

Radio frequency emissions were observed from this plasma at frequencies consistent with the geometric mean emission process over a significant range of operating conditions. Emission data were taken for several background gases to test the predicted inverse fourth root mass dependence. Our experimental data were consistent with this functional dependence. An experiment was performed in which the proportion of helium and argon in the background gas was varied from 0 to 100% and back again to 0%. The geometric mean emission peak appeared separately at frequencies appropriate for each gas, with the amplitude of each proportional to the gas concentration. There was not, in these experiments, a single peak which moved in frequency in proportion to the average ion mass in the emitting plasma.

Plasma Turbulence and Non-Linear Mode Coupling

At a paper presented at the APS Division of Plasma Physics Annual Meeting in New York City in October 1981, an abstract of which is on page G-5 of Appendix G, we reported new data on RF emissions and nonlinear mode coupling from the modified Penning discharge plasma. We also investigated the process of ion thermalization as a function of the magnetic field strength and particle number density. It was found that the degree of nonlinear mode coupling in the RF spectrum increased with increasing magnetic field strength, and that the degree of ion energy thermalization (measured with a retarding potential energy analyzer) increased with the level of RF activity, and was greater at lower particle number density. The RF emission peaks produced by this plasma appeared to be the electron plasma frequency at low (less than 10^8 particles per cubic centimeter) plasma densities, and the geometric mean emission frequency and multiple harmonics of it at number densities higher than a few times 10^8 particles per cubic centimeter.

Some of the results relating to nonlinear mode coupling were both interesting and surprising. One such observation is the production of multiple harmonics of a fundamental frequency, as the result of intense nonlinear mode coupling. An example of this is shown in Figure 6. This shows a spectrum of RF emissions picked up by a small coaxial waveguide probe near the plasma, with a linear vertical scale, and a horizontal linear frequency extending from 0 to 200 megaHertz. In this example, at least 23 harmonics of the fundamental are visible, including several harmonics in the FM frequency band near 100 MHz, which can be picked up by FM receivers in Ferris Hall on the UTK campus. Under this and similar conditions of operation, the steady-

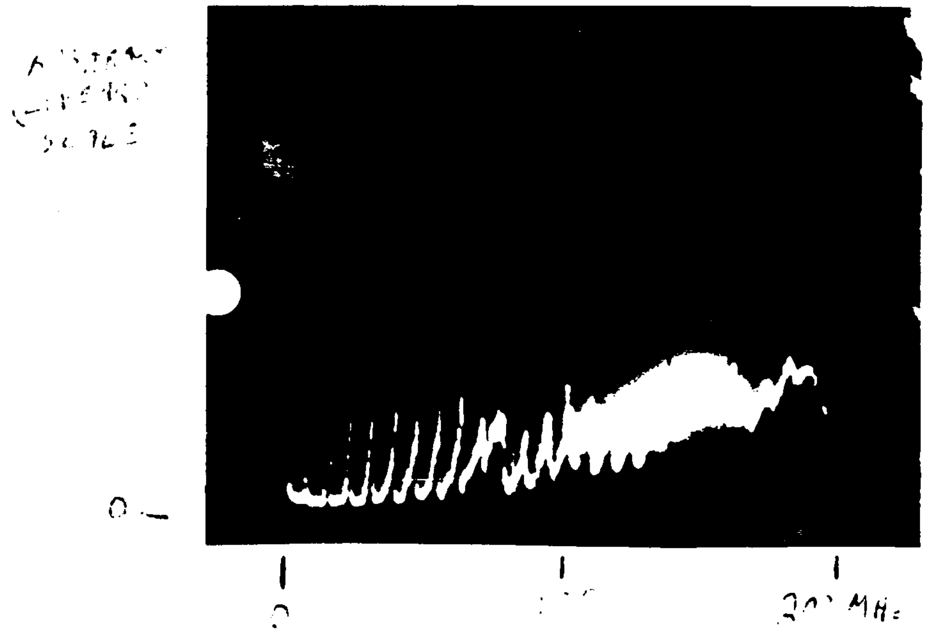


Figure 6

state plasma produces higher amplitudes for the odd harmonics than for the even harmonics, at least at low frequencies. The multiple harmonic production is very definitely not due to nonlinear saturation of the detector. A modified Penning discharge operated under these conditions might provide a useful noise source for electronic countermeasures or jamming, and it certainly provides an excellent test bed for the investigation of nonlinear mode coupling.

Observation of Hot Ions

In addition to the above observations, we saw experimental evidence of hot ions with kinetic temperatures ranging from a few hundred eV up to several keV on a retarding potential energy analyzer which detects the axial component of ion energy; on Doppler line broadening measurements which look at the perpendicular components of ion velocity; and from data taken in the ion saturation regime of a Langmuir probe, which responds to the isotropic distribution of ion kinetic temperature. We found evidence, mentioned in the abstracts of the papers included in Appendix G on pages G-5 and G-7, that the non-linear mode coupling present in the plasma and the degree of thermalization of the ion energy distribution function are linked. The mode coupling and thermalization of the ion energies are both enhanced at low plasma number densities and low background pressures, when the levels of electrostatic turbulence are highest.

The Modified Penning Discharge as an Ion Source

An unanticipated finding of this research program was that the modified Penning discharge can serve as a source of hot ions with kilovolt energies, in which the energy distribution function of these ions can be adjusted to almost any desired form by suitable changes in the operating characteristics of the plasma. The ability of the modified Penning discharge to produce Maxwellian ion energy distribution functions with kilovolt kinetic temperatures is well known, and was reported by the Principal Investigator and other authors as early as 1965. It has not been realized, however, that the shape of the distribution function itself can be varied over a wide range of possibilities by suitable adjustment of the discharge parameters, such as magnetic field strength, neutral background gas pressure, gas type, electrode voltage, and geometry.

A sample of the wide variety of energy distribution functions which can be produced in this modified Penning discharge are shown on Figures 7a-c, which are output data from the retarding potential energy analyzer located on the axis of the plasma. This analyzer yields the integrated ion energy distribution function of ions which are lost through the magnetic mirror throats. Figure 7a shows an approximately Maxwellian energy distribution function, Figure 7b shows an approximately monoenergetic distribution function with ion energies of 4500 eV, and figure 7c shows a distribution function which is constant from 0 eV to about 5300 eV. This latter distribution function would be very difficult to produce if one deliberately set out to do so. A flat distribution function of ions over all energies from 0 to

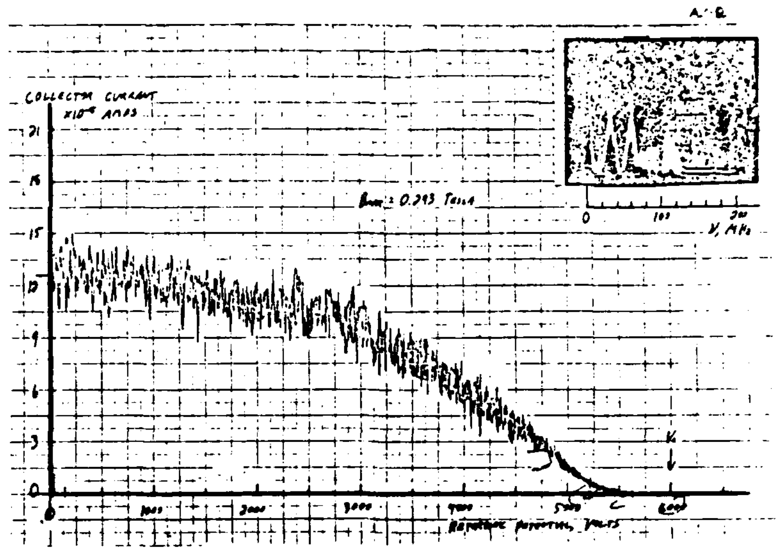


Figure 7a

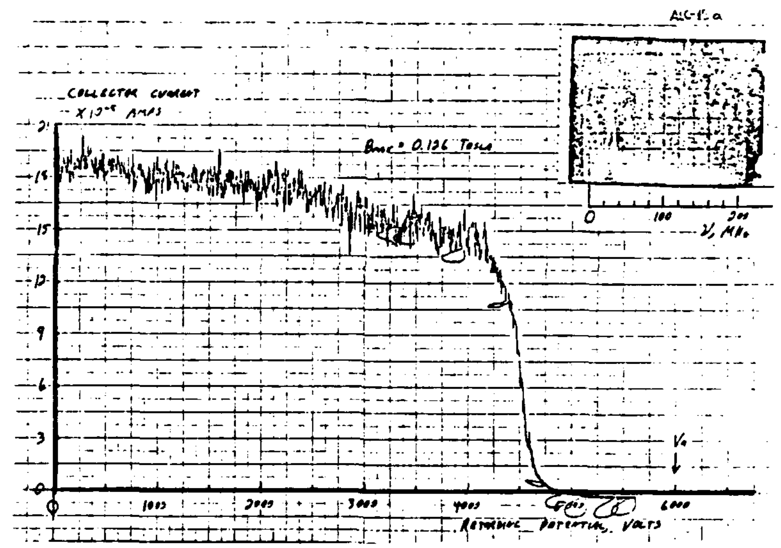


Figure 7b

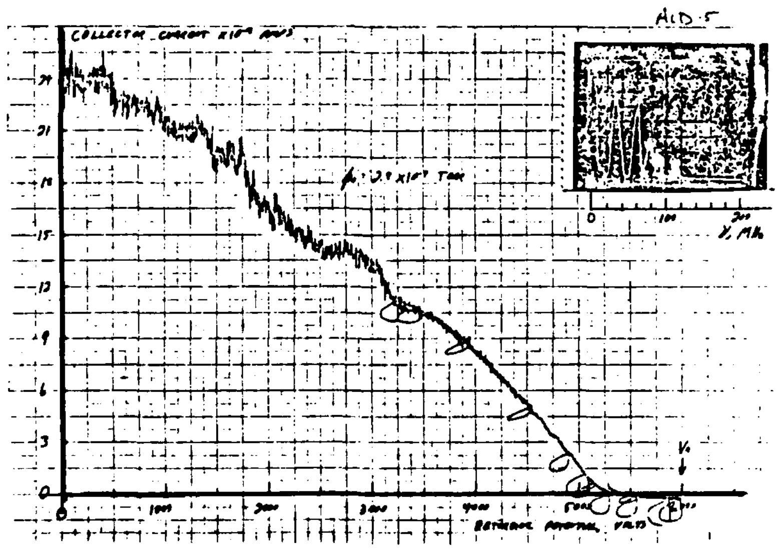


Figure 7c

nearly 6 keV might be useful in specialized applications, and would be extremely difficult to produce by any other means.

Exploratory Studies

When operating the modified Penning discharge in argon gas, we observed an interesting phenomenon in the RF emission spectrum. At background pressures of about 8×10^{-5} Torr of argon, maximum magnetic fields of 0.3 Tesla, an anode voltage of 3 to 5 kilovolts, and an anode current of 30 milliamps, the RF spectrum was virtually flat over the range from 0 to 1 gigaHertz, and was free of prominent emission peaks. This flat spectrum implied that the plasma was emitting white noise over this entire frequency range, and perhaps beyond 1 gigaHertz (the upper limit of our spectrum analyzer). The emission was initially detected with a coaxial waveguide antenna in the near field of the plasma. We later looked at this RF emission several wavelengths from the plasma, and found that the RF noise was evident in the FM band from 88 to 106 megaHertz. In the near field, the AM radiation was also prominent in the vicinity of 1 megaHertz.

This white noise emission spectrum is an extreme limit of the multiple harmonic nonlinear mode coupling which had been observed earlier, and raises a variety of interesting basic physics questions. First of all, any physical process which is capable of such broadband emission would certainly have implications for military and other communications if it occurred in the magnetosphere or in astrophysical contexts. Secondly, the physics of this broadband emission is presently unknown, and may even represent a new

physical phenomenon, as opposed to an unfamiliar manifestation of some familiar physical process.

Theoretical Research

The Principal Investigator has played a coordinating and supporting role in a collaboration on theoretical research with Professors J. Douglas Birdwell and Igor Alexeff of the UTK Electrical and Computer Engineering faculty during this period. During the early part of this period, we completed theoretical computations of the Fried-Conte dispersion function relevant to two interpenetrating electron beams with finite background ion temperature. This required a computer solution, the parameter of which was the ratio of ion thermal velocity to the electron beam velocity. Some of the results of this computation were published in the Physics of Fluids reprint included in Appendix E, on page E-1 of this report. In summary, it was found that neither the frequency nor the existence of growing waves was affected in any important way until the ion thermal velocity became comparable to the electron beam velocity.

We also summarized in the Physics of Fluids reprint theoretical computations, due to Professor Igor Alexeff, of the effective plasma conductivity due to the interpenetrating electron beam interaction. It was found that in deuterium gas, the conductivity due to the two interpenetrating electron beam interaction is 166 times smaller than the conductivity to be expected from the Buneman beam-plasma interaction.

Publications

During this 21 month period, seven publications and/or conference presentations were supported by this contract, and were so acknowledged. Reprints or abstracts of these publications are included in Appendices E and G of this report. A major discovery paper in the Physics of Fluids has been mentioned previously, and attracted a great deal of interest and attention. There were five presentations at major plasma meetings, including a paper on the ion mass dependence of RF emissions at the geometric mean plasma frequency, presented at the 1981 IEEE International Conference on Plasma Science in May, 1981 (Appendix G, page G-4). We presented two papers at the 23rd Annual Meeting of the Plasma Physics Division of the American Physical Society in October, 1981 in New York City (Appendix G, pages G-5 and G-6). One of these (G-6) was related to the macroscopic stability of electric field dominated mirror plasmas and is entitled "Radial Equilibrium and Force Balance in Electric Field Dominated Plasmas". This paper brought to bear experimental evidence that macroscopic stability of electric field dominated mirror plasmas results from the inward force on ions due to the radial electric field being stronger than the outward centrifugal forces that drive the Rayleigh-Taylor flute instability.

At the APS meeting we also presented a paper on RF emission, nonlinear mode coupling and ion thermalization in a modified Penning discharge plasma (G-5). This reported exploratory observations on multiple harmonic production in the modified Penning discharge plasma made in the Summer and Fall of 1981.

We had two papers at the 1982 IEEE International Conference on Plasma Science in Ottawa, Canada in May (Appendix G, pages G-7 and G-8). One of these is a comparison of high frequency RF emissions from two configurations of electric field dominated plasma (G-7). In this paper, we compared and contrasted the RF emissions observed in the modified Penning discharge plasma supported by ONR, with the classical Penning discharge configuration (which does not operate in a magnetic mirror geometry) supported by our AFOSR contract. Also at the IEEE meeting, we presented a paper (G-8) on stabilization of the flute instability by a DC electric field, of which Professor Igor Alexeff is the first author, and which carries forward some of the ideas which were discussed by myself on the stability of electric field dominated mirror plasma at the APS meeting in October, 1981.

Finally, Appendix E includes a paper (E-11 to E-13) which was presented at the International Conference on Plasma Physics in Goteborg, Sweden in June, 1982. This paper is an expansion of that which was presented at the IEEE meeting in May, and describes a paired comparison of high frequency RF emission from two configurations of electric field dominated plasma. This paper was supported jointly by the ONR and AFOSR contracts, and contrasts the RF emissions observed in these two experiments.

Accomplishments of the FY 1983 Research Program

<u>Apparatus Modifications</u>

It originally had been our intention to replace the oil difusion pump with a turbomolecular vacuum pump costing about $5000 before the end of FY

1982. However, the desirability of purchasing a used Biomation 8100 transient recorder for the transient data handling system made it necessary to reallocate equipment money intended for the turbomolecular pump to the purchase of a used but serviceable Biomation 8100 transient recorder. The total cost of the transient recorder was $7500, which was shared equally between the ONR and AFOSR contracts. The necessary approvals were processed at the time of the purchase, in the Fall of 1982.

In the late summer of 1982, a high voltage Langmuir probe capable of being moved along the plasma axis was installed and put into operation. The first data, taken during the period up to January, 1983, were of the axial profile of floating potential taken with the Langmuir probe. In some cases, we observed axial electric fields in excess of 150 volts per centimeter. Simultaneously with these profiles we took data on RF emissions and axial ion energy spectra from the retarding potential energy analyzer. These data were taken from August 1982 to October, and were presented at the APS plasma physics meeting in New Orleans in November, 1982. An abstract of this paper is in Appendix G on page G-9.

During the period from November 1, 1982, to April, 1983, two new research assistants were familiarizing themselves with the apparatus and conducting a series of exploratory runs which led to design modifications of the Langmuir probe. These changes were intended to minimize perturbations of the plasma characteristics brought about by the presence of the probe itself. These modification not only resulted in a superior Langmuir probe design, but the associated development work also led to simplification and redesign of the anode and cathode structures.

In January, 1983 a new, half-time graduate research assistant was hired on the Navy contract and assigned the responsibility of putting back into service an analog-to-digital data handling system for measuring plasma fluctuations. This system was among the diagnostic instruments that were obtained from NASA for use on this and the AFOSR contracts. The hardware in this system had been idle for 5 years, and several transistors and other solid state components required replacement as the system was checked out and made serviceable. This data handling system was ready for operation by September, 1983.

During the period from April to June, 1983, favorable experience with certain modifications on the AFOSR experiment led us to disassemble the ONR apparatus and modify the geometry of the anode and cathode. These modifications included additional provisions for cooling the cathodes of the discharge, where the greatest heat deposition takes place, and were intended to make possible higher anode currents and electron number densities in the plasma. Also during this time, the retarding potential energy analyzer and the Langmuir probe systems were decoupled so that they use independent power supplies and can be operated simultaneously. The vacuum system was reassembled and put back into service in mid-May, 1983. As hoped, the plasma operated in a new regime with up to 500 watts of steady-state power input, 0.4 amperes of current, and number densities that can exceed 3×10^{10} particles per cubic centimeter throughout the plasma volume.

During the period covered by this status report, the contract provided for 2 half-time research assistants. Mr. Paul Hayman, who had been the senior research assistant, received his bachelor's degree in electrical engineering in

December, 1982. He was admitted to graduate school as a candidate for a degree of Master of Science in Engineering Science and Mechanics as of January 1. Paul Hayman was replaced with Mr. Peyman Dehkordi, a Master of Science in Electrical Engineering degree candidate who is familiar with digital systems, both hardware and software. Mr. Dehkordi was assigned responsibility of refurbishing, and placing back into operation, the hardware and software associated with a 3 channel analog-to-digital data handling system that was built at the NASA Lewis Research Center for plasma turbulence research. Mr. Dehkordi made satisfactory progress with his task, and the data handling system was ready for operation by the end of the summer, 1983. The second half-time assistan to join the ONR contract, Mr. Blair Finkelstein, obtained his second bachelor's degree, in Electrical Engineering, in December, 1982. After completing one quarter of graduate work at UTK, he left to pursue advanced studies in electro-optics at the University of Arizona at Tuscon in April, 1983. Mr. Finkelstein was replaced by Mr. Paul Spence, a doctoral student in the UTK department of Engineering Science and Mechanics. Mr. Spence has his master's degree in that field, and has a career interest in the field of high temperature plasma physics. Mr. Spence has been senior research assistant on the ONR contract since Mr. Finkelstein's departure on April 1, 1983.

Initial Experimental Results

During this period, the ONR magnet facility was set up to produce a modified Penning discharge configuration, in which the magnetic field is an axisymmetric mirror configuration with a minimum at the midplane about

1/6 of the maximum magnetic field on the axis, under the coils. The modified Penning discharge was operated with a magnetic field up to a 0.4 tesla on the axis, under the mirror coils, and produced a plasma about 10 centimeters in diameter at the midplane, and about 120 centimeters long. The plasma was operated in the steady state with helium and argon gas, and the glass vacuum system allowed RF radiation to escape.

Axial Profiles of Floating Potential

The preliminary findings reported at the Goteborg meeting in June, 1982 (see pages E-11 to E-12), were followed up in late 1982 by a series of investigations of the axial floating potential profile and the ion energy distribution functions in this modified Penning discharge. These finding were reported at the APS Plasma Physics Division meeting in November, 1982. The abstract of this presentation is included in Appendix G, on page G-9. For these investigations, the magnetic field distribution was the same as that used previously, an axisymmetric magnetic mirror with a 6:1 mirror ratio. The emphasis in these investigations was the simultaneous measurement of the floating potential profile along the axis of the discharge (to estimate the magnitude of the axial electric field); and the axial ion energy distribution function, with the retarding potential analyzer located beyond the cathode at one end of the discharge.

A characteristic experimental run, with a high background pressure and density of helium gas, showed an axial electric field which was extremely small throughout most of the discharge. The radial potential drop at the midplane was small also, only about 150 volts from the anode to the axis. The potential dropped off in a sheath near the cathodes in the region of low number density at either end of the discharge. This axial electostatic potential profile gave rise to a monoenergetic ion energy distribution function, in which the ions left the discharge at energies essentially equal to the anode voltage.

As the background pressure of the helium gas was lowered, the axial profile of electrostatic potential changed dramatically. In this case, the axial potential decreased exponentially with distance from the midplane. The axial electric fields were as high as 75 volts per centimeter in the vicinity of the midplane. The ion energy distribution function for this potential profile was much broader. The best-fitting integrated ion energy distribution function for a characteristic example had a kinetic temperature of about 390 electron volts.

As plasma operating conditions, including the background gas pressure and anode voltage, were adjusted about the values discussed above, an interesting structure began to appear in the axial potential profile. The axial potential profile was no longer monotone decreasing, but had a small plateau in the region between the midplane and the cathode. The energy distribution function corresponding to this axial potential profile had a monoenergetic component with energies very close to the anode voltage of 3600 volts, and a thermalized component with a kinetic temperature of a few hundred electron volts.

Perhaps the most interesting axial potential profile of all, however, was a radial potential drop from the anode to the axis in the midplane of about 1600 volts, indicating a very strong radial electric field, <u>and</u> an electrostatic potential well <u>along the axis</u> of the discharge with a depth of 300 volts, which is capable of trapping ions up to this energy. The existence of a local electrostatic potential well for ions should be of interest to the DoE mirror program, because it has been generated by a very simple configuration of axisymmetric coils. This potential well does not require end plugs, neutral

beam injection, or any other of the extreme technological measures required to produce an axial potential well for ions in the tandem mirror concept.

Axial Profiles of Plasma Characteristics

The exploratory data just discussed, and presented at the APS Plasma Physics meeting in New Orleans in November, 1982, was considered sufficiently interesting to justify measuring axial profiles of plasma characteristics from a succession of Langmuir probe traces taken along the axis of the modified Penning discharge. This was done in April and early May 1983, and reported at the IEEE International Conference on Plasma Science held in San Diego, CA on May 23-25, 1983. A copy of the abstract of this paper is included on page G-10 of Appendix G.

The key data observed during measurement of the longitudinal profiles of floating potential held up under more detailed examination when axial profiles of plasma parameters were plotted from the Langmuir probe traces. A characteristic experimental run was taken at high background neutral gas pressures, and, as in the previous case, showed a very low radial potential drop from the anode ring to the axis, no more than 100 volts, and very close agreement between the floating and plasma potential. This small difference is a consequence of the relatively low electron kinetic temperatures in this plasma, a few 10's of electron volts.

As the background pressure was lowered, the axial electric field became larger. Again, there was good agreement between the floating and plasma potential, and in this case the electric fields penetrated substantially into the plasma. At still lower pressures, there was a greater difference between the

floating and plasma potentials at a given axial station, but there was also a significant axial electric field along the entire discharge, with the electric field strength characteristically about 150 volts per centimeter along the discharge axis. Under other conditions, an electrostatic potential well for ions developed. This was confirmed by reference to the plasma potential, as well as the floating potential profiles of the plasma. The electrostatic potential well for ions along the discharge axis was accompanied by a local anomaly in the axial ion number density and electron kinetic temperature profiles.

High Power Mode Results

Further experimental data were taken after June, 1983. On Figures 8 and 9 are two RF emission spectra taken when the plasma was operating in the new, high power mode made possible by the apparatus modifications discussed above. The first of these shows the emission spectrum from 0 to 1.2 gigahertz. The vertical scale is 10 dB per division. The intensity of RF emissions are approximately a factor of 100 higher than they were in the lower density and lower current configuration operated earlier. The emission shown in Figure 8 is relatively flat from 200 MHz to the upper limit of 1.2 GHz. The structure on the RF emission spectrum is not random in character or due to inadequate video filtering; retracing of the spectrum with a manual scan shows that the peaks are reproducible, and present in the steady-state. These peaks are harmonics of the geometric mean emission frequency, the fundamental of which is about 20 megahertz. The peak at approximately 1200 megahertz is consistent with the 60th harmonic of the fundamental frequency.

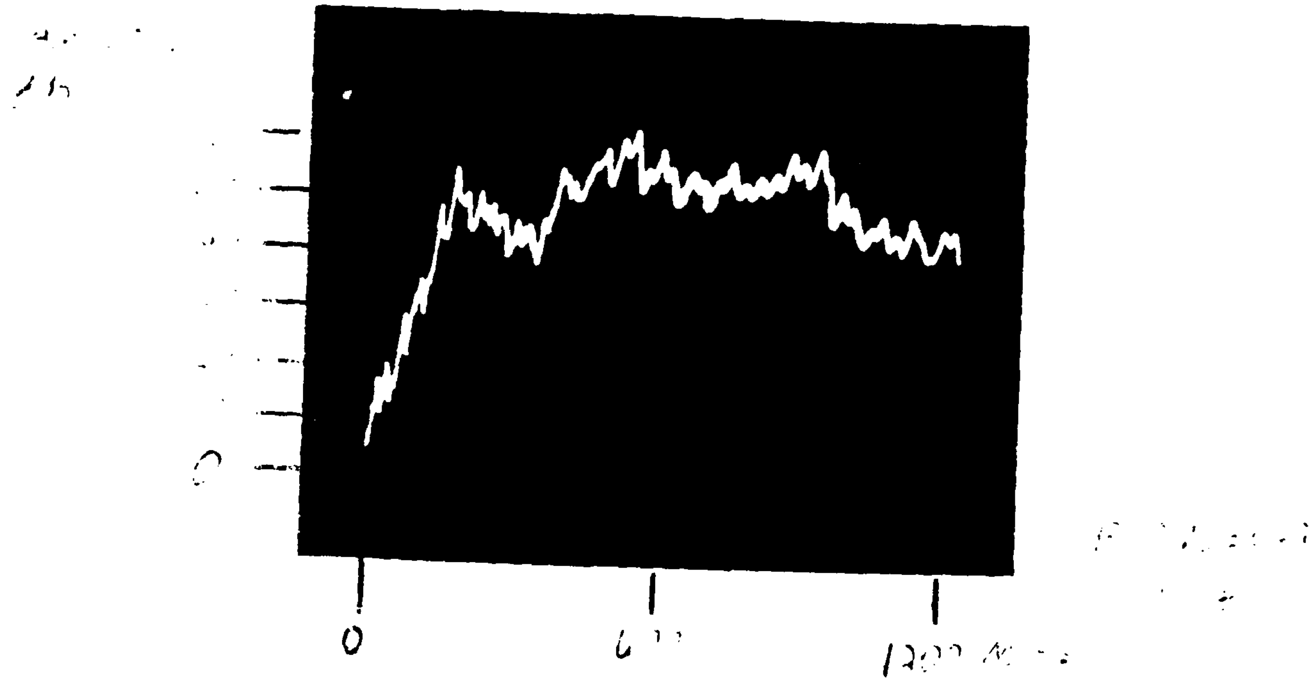


Figure 8

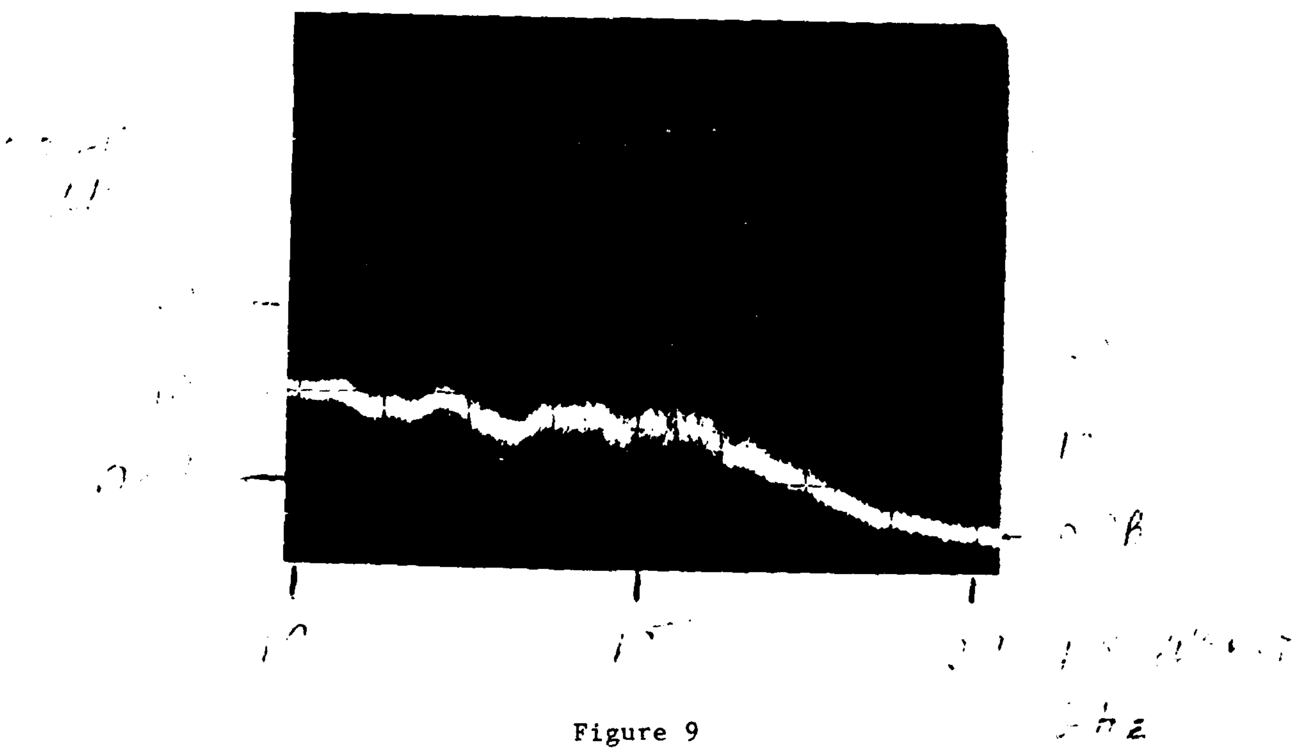


Figure 9

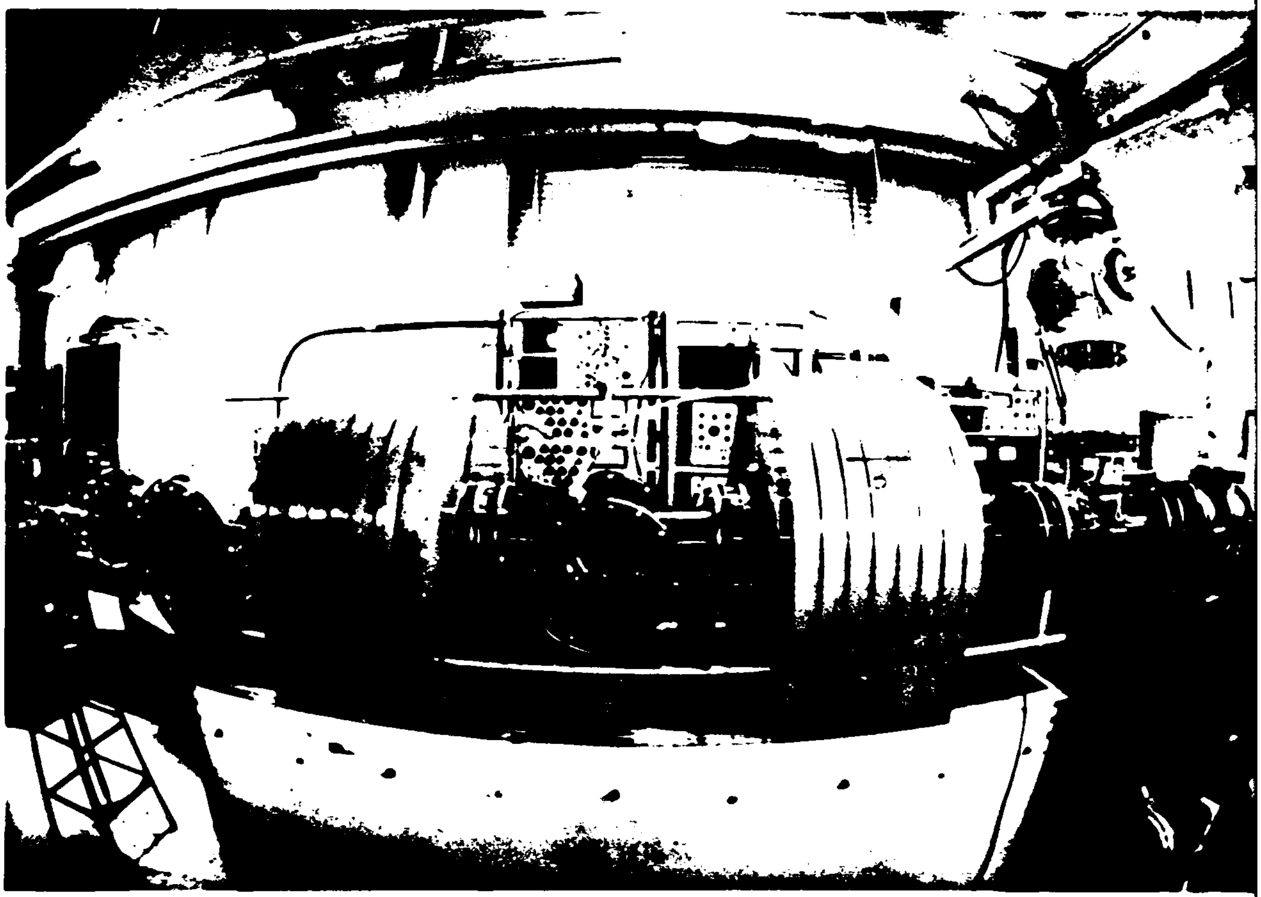


Figure 10

To determine the upper frequency limit of the RF emission from this plasma,we borrowed from Professor Igor Alexeff the high frequency spectrum analyzer which he purchased under his AFOSR contract. On Figure 9 is shown an RF spectrum over the range from 1.0 gigahertz to 2.0 gigahertz. The instrument does not respond below 1 gigahertz.

Accomplishments of the FY 1984 Research Program

Apparatus Modifications and Instrumentation Development

On Figure 10 is a photograph of the modified Penning discharge used on the ONR contract, which was taken in mid-1983. The two water cooled copper coils which generate the magnetic mirror configuration are visible to the right and left of the center of the photograph. The vacuum system is made of six inch (15 centimeter) diameter glass pipe, to allow the free escape of RF radiation from the plasma. The diffusion and fore-pump are off to the right side of Figure 10. The anode ring is visible through the view port on the midplane. The anode consists of two circular water-cooled copper rings separated by one inch in the axial direction. The quarter-inch copper tubing is cooled by water from the building water supply. Behind the apparatus are equipment racks which contain the polarization diplexing microwave interferometer; the data handling system for fluctuation measurements; and vacuum gauges and service equipment for the vacuum system, including a quadrupole mass spectrometer. As is evident from this photograph, there is ample visual and experimental access to the plasma volume between the two magnetic field coils.

Figure 11 is a view of the portion of the UTK Plasma Science Laboratory which houses the ONR apparatus. In the foreground are the fore-pumps, the diffusion pump, and the freon cold trap which allows us to maintain a base pressure in the vacuum system of 2×10^{-6} torr. The large power supply on the right hand side of the photograph energizes the magnetic field coils and can provide up to 40 kilowatts of dc power. At this level of power input, the maximum magnetic field on the magnetic axis is 0.4 tesla.

This electric field dominated plasma, from which we are observing RF emissions, is a modified Penning discharge in a magnetic mirror configuration with a 5:1 mirror ratio. This relatively high mirror ratio was chosen to better simulate the high mirror ratios characteristic of the earth's magnetosphere. This plasma is unlike plasmas investigated in many other academic laboratories (and is like magnetospheric plasmas) in at least two respects; 1) the plasma is operated in the steady state, thus providing an opportunity to take accurate experimental data even in the presence of high levels of noise and plasma turbulence; and 2) the modified Penning discharge plasma is penetrated by strong electric fields, both radially and axially.

During this period, a firm infrastructure was built for our continuing experimental investigations of plasma turbulence, anomalous resistivity, and RF plasma emissions. We put into service a polarization diplexing microwave interferometer; a Langmuir probe system capable of operating in plasmas which float several kilovolts above ground; a 1/2 meter Fastie-Ebert visible spectrometer; a broad-band RF antenna with a frequency response flat to within $\pm$ 1 dB over 0.1-12 GHz; a two-channel analog-to-digital data handling system; and a retarding potential energy analyzer with which we routinely

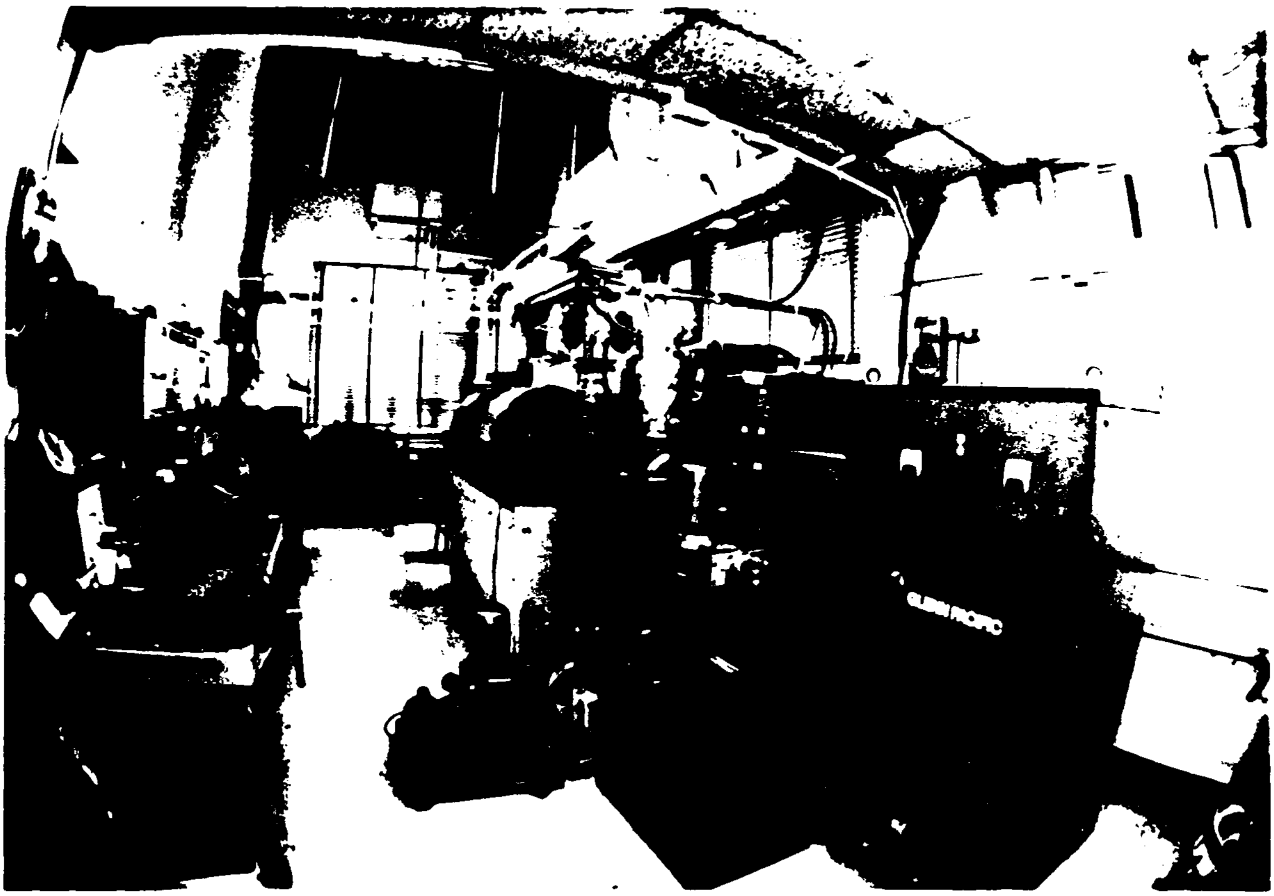


Figure 11

measure the energy distribution functions of ions leaking out the ends of the magnetic mirror. We also continued the development and refinement of probes and antennae for measuring RF emissions over a wide range of frequencies up to and beyond 1 gigaHertz.

Summary of Research Program

During this fiscal year, the contract supported two half-time research assistants. Mr. Peyman Dehkordi, a Master of Science in Electrical Engineering degree candidate, who is familiar with digital systems, continued to work on recommissioning the two-channel analog-to-digital data handling system. He also brought into operation the associated computer software required to obtain autopower spectra, cross power spectra, and other statistical data from two simultaneously sampled digital time series, provided by capacitive probes and other diagnostic instrumentation. The data handling system was available for operation a the beginning of this period, and the associated software and signal conditioning hardware were fully operational in June, 1984.

In September, 1983, Mr. Dehkordi was transferred to the AFOSR contract, and Mr. Saeid Shariati was hired to develop plasma diagnostic software for the LeCroy 3500 transient recording system, which was purchased with the $30,000 in equipment funds provided by ONR in the summer of 1983. Mr. Shariati developed these computer programs as part of his thesis for the Master of Science in Electrical Engineering degree, which was awarded in March, 1985.

During this year, Mr. Paul Spence, a candidate for the Ph.D. in the Department of Engineering Science and Mechanics, was assigned the responsibility of Principal Research Assistant on the ONR contract. Mr. Spence's interests are very strong in RF emission and microwave diagnostic technique, and he made substantial progress in developing antennas for broadband, absolute measurement of RF emission from the plasma during this year. In the Summer and Fall of 1983, Mr. Spence made axial and radial profiles of the plasma parameters, from Langmuir probe data, and these were correlated with the RF emissions from the plasma. These results were described in a paper given at the APS Plasma Physics Division meeting, which is included in Appendix G, on page G-11. During the winter and spring quarters of 1984, Mr. Spence put into operation the broadband, calibrated antennas which he developed, and reported the first results of the absolute RF emission measurements from the modified Penning discharge plasma at the IEEE meeting in St. Louis in May, 1984. Abstracts of these papers are in Appendix G, on pages G-12 and G-13. RF emission measurements from the ONR experiment also were presented at the International Conference on Plasma Physics, held in Lausanne, Switzerland at the end of June, 1984. A reprint of this paper is in Appendix E, pages E-42 to E-45.

We set a new standard in broadband, absolute, far-field Rf emission measurements from energetic plasmas in the UTK Plasma Science Laboratory during this contract year. To assist our colleagues in other laboratories, the details of the broadband, calibrated antennas which we developed for this contract were described in a diagnostics paper at the IEEE meeting in May, 1984 (page G-13, Appendix G). The software programs

developed for the LeCroy 3500 transient recorder system were also described at that meeting (pages G-12, Appendix G) and made available to several groups who expressed an interest in applying this software in their diagnostic program.

Experimental Results

The results of our experimental program during this period are summarized in the abstracts and papers included in appendices E and G of this report. On page G-11 is shown the abstract of our paper, supported entirely by this ONR contract, which was presented at the 25th Annual Meeting of the APS Division of Plasma Physics in Los Angeles, California, in November, 1983. The title of this paper was "Axial and Radial Profiles of Plasma Parameters in an RF Emitting Modified Penning Dsicharge" by Paul Spence and myself. A characteristic feature of the modified Penning discharge, in addition to strong radial and axial electric fields and high levels of fluctuations and electrostatic turbulence, is operation in two modes of behavior. These are evident on the current-voltage plot reported in this paper. This behavior was anticipated, and found, during the course of early experimental investigations of the modified Penning discharge used for this contract (page G-5). This nonlinear behavior has recently been investigated in more detail by Merlino and Cartier of Iowa, who also observed this nonlinear mode transition in a Penning discharge plasma which they were investigating under ONR contract (N00014-83-K-0452).

Our paper at the APS Meeting presented investigations of the effect of the background neutral particle number density and the electron number

density on RF emission; on the nature of the axial and radial plasma potential profiles; and on the radial profiles of electron number density and temperature. In tnis paper, we investigated the RF emission from an experimental run which was operated at relatively low background pressures of helium gas, and high anode potentials. This discharge emitted RF radiation at multiples of the geometric mean emission fequency. There were significant axial electric fields, as high as 200 volts per centimeter near the midplane, representing a very significant anomalous resistivity. Both the plasma potential, obtained from Langmuir probe curves, and the floating potential of the probe are self-consistent. The axial number density profile under these conditions sharply peaks at the center of the discharge.

The radial profile data, taken at the mid-plane of the discharge, indicates a relatively hollow plasma, with electric fields pointing radially inward. Under these conditions, the axial component of the ion energy was about half way thermalized, with an effective energy of about 1.8 keV. About half the energy distribution function was monoenergetic or beam-like, at a potential very close to the anode potential of 6 kilovolts for this experimental run.

At a background neutral gas pressure about twice that of the previous run, the RF emission was more intense, and showed harmonics of the geometric mean emission frequency, and a maximum in the envelope of the RF emission in the vicinity of the electron plasma frequency. RF radiation was visible out to about 800 megaHertz in this case. The axial potential profile for this set of run conditions was relatively flat compared to the previous case, with relatively small axial electric fields in the bulk of the

discharge. The electron number density was concentrated toward the midplane of the discharge. The electron kinetic temperature was on the order of 5 to 9 electron volts. With the bulk of the plasma at these higher number densities, the radial potential profile varied little, and had only a small radial electric field. The ion energies form this discharge were about 80% monoenergetic, at the anode voltage of about 2 keV.

These data, presented at the 1983 APS meeting, were the first to employ our conical spiral antenna. This allowed us, for the first time, to see clearly the plasma emissions without the modulation of the antenna response pattern. Further development of our broadband, calibrated antennas was described at the IEEE International Conference on Plasma Science, held on May 14-16, 1984 in St. Louis, Missouri. The abstract describing this development program, which was supported half by ONR and half by AFOSR, are included in Appendix G, on page G-13.

A paper which summarized our experimental results from November thru May, 1984 was presented at the 1984 IEEE meeting, and was entitled "Broadband RF Emission and Electron Number Density Measurements of An Electric Field Dominated Plasma" by Paul Spence, Professor David Rosenberg and myself. This paper was entirely supported by the ONR contract. The abstract of this paper is on page G-12.

The major thrust of this paper was absolute power measurements of the far-field RF power flux from the modified Penning discharge, using a calibrated conical spiral antenna and a calibrated planar log spiral antenna. These antennae have approximately constant effective apertures over the frequency range of interest, from about 100 megaHertz to 1.2 gigaHertz. The

conical spiral antenna was located 2.2 meters to 2.9 meters away from the plasma under a variety of plasma operating conditions. The planar spiral was located from 2.5 meters to 3.1 meters away from the plasma during power measurements. The net power captured by these antennas from 100 megaHertz to 1.2 gigaHertz was measured using an HP 432A power meter with a HP 478A thermistor mount. A 1000 megaHertz low pass filter was inserted, and for the conditions studied, less than 10% of the detected power was above 1 gigaHertz. Due to polarization, a 3dBm correction was added to the detected power, as well as a 1 dBm correction for cable losses. Based on measurements at several locations, the plasma was taken to radiate power isotropically, and consequently the RF power was taken to be the local power flux of the antenna, integrated over 4π steradians. This radio frequency power was plotted as a function of the input power to the plasma. The efficiency of the plasma as a microwave source was plotted. The data indicate that the RF power emited was directly proportional to the input power to the plasma.

We also presented data showing the emitted RF power as a function of the electron number density. The high power mode data is consistent with a linear dependence of the total radiated RF power, on the electron number density. This is important from a theoretical point of view, because these data imply that the RF emission which we observed in the far field is due to <u>incoherent</u> radiators, and not coherent emission, which would be proportional to the square of the electron number density. These incoherent emitters are individual electrons which are radiating in this highly turbulent discharge. The data also indicated that the radiating efficiency of this discharge

decreases with anode voltage, and with input power to the plasma. This is probably a coincidence of these first preliminary data on absolute power measurements. It will be interesting to vary the plasma parameters and see whether higher efficiencies can be obtained under other conditions for which the plasma parameters are optimized for maximum efficiency.

Listed in Appendix F is the paper on the software developed by Mr. Saeid Shariati, for the LeCroy 3500 transient recorder system. An abstract of 3500 this poster paper, presented at the IEEE Plasma Science Meeting in May, 1984 included in Appendix G and may be found on page G-29.

Finally, a paired comparison paper was prepared on the RF emission, plasma wave propagation, and plasma turbulence characteristics of the classical and modified Penning discharges oeprated in the UTK Plasma Science Laboratory for the AOFSR, and ONR, respectively. My travel to the 1984 International Conference on Plasma Physics in Lausanne, Switzerland, on June 27-July 3, 1984, was supported by the AFOSR. This paper describes a comparison of the two forms of Penning discharge, based on the diagnostic methods which have been developed over the past year under both the ONR and AFOSR contracts. A four page summary of this international conference paper is included in Appendix E, on pages E-42 to E-45.

Accomplishments of the FY 1985 to FY 1987 Research Program

Objectives for this Contract Period

In the renewal proposal for the three year period commencing on October 1, 1984, which was submitted on June 22, 1984 as Plasma Science Laboratory report PSL 84-2, three major items were proposed for investigation during the

three year period which expired on September 30, 1987. We will examine these three proposed areas of research, and progress toward the proposed objectives will be described. The objectives of this contract were as follows:

1. It was proposed to extend our measurements of the absolute RF power emitted by the modified Penning discharge by using the calibrated, broadband antennae which we developed immediately prior to the beginning of this three-year period. We proposed to measure the RF emission power in absolute units, as a function of plasma parameters such as electron kinetic temperature, the electron number density, and the neutral background gas pressure. We also proposed to measure the absolute efficiency of generation of RF power from these discharges over the very broadband frequency range observed.

2. We also proposed to measure the propagating waves, fluctuations, and turbulence in the modified Penning discharge using the two-channel, analog-to-digital data handling system developed previously. In addition to implementing the analog-to-digital data handling system and obtaining auto power spectra, cross power spectra, coherence spectra and phase spectra from two channels of time series data, we also proposed to apply microwave scattering techniques, which were developed by a master's degree candidate on the AFOSR classical Penning discharge, to the ONR modified Penning discharge. It was proposed that this microwave scattering data provide further information about plasma fluctuations and turbulence, particularly the extent to which the plasma fluctuations are coherent, and under what conditions.

3. Finally, it ws proposed to use the Hewlett Packard Model 8510 high infrequency microwave network analyzer to measure the effective collision frequency of the electrons in the plasma. The assumption of binary collisions, which underlies the classical Lorentzian gas calculation and neoclassical transport calculations in fusion research, was suspected to be unsatisfactory in highly turbulent, high temperature plasmas of interest for many DoD and DoE applications, including fusion research. In a highly turbulent plasma, the momentum vector of the electrons is at least as likely to be deflected by interactions with fluctuating, microscopic electric fields as it is by binary Coulomb collisions with other charged particles. In the proposal of 1984, it was pointed out that a possible mechanism to measure the effective collison frequency may be provided by the Appleton equation, which describes the propagation of electromagnetic radiation in a magnetized plasma in which there are collisions. It was pointed out that by irradiating a test plasma with the extraordinary mode of propagation, and measuring the absorption of the extraordinary mode of propagation near the electron gyrofrequency, one should be able to make a direct experimental measurement of the effective collision frequency, which is proportional to the full width at half maximum of the resonant absorption peak near the electron cycloron frequency.

It is now possible to report that item number 1 above was done, and produced results which were definite and quantitative, but which indicated that the efficiency, and absolute magnitude of RF emissions from Penning discharge plasmas, were too low to be of likely interest or relevance to DoD applications. Moreover, the functional dependence of the efficiency and power emitted, on such plasma parameters as electron number density, were such

that the efficiency and emitted power were decreasing with increased power in put to the plasma and increased plasma number density.

The research proposed in items 2 and 3 above have produced interesting, even exciting, results which are being written up in Mr. Paul Spence's Ph.D. thesis, which is supported by this contract. He expects to graduate in August, 1989. These results are described briefly below.

Apparatus Modifications, FY 1985-87

During this three-year period, several important improvements were made to the ONR experimental apparatus. The vacuum system was upgraded with new equipment, the pruchase of which was paid for by funds from the ONR contract of the previous year. The old, unreliable ion gauge readouts were replaced with new units which have automatic ranging. These units use the same ion gauge tubes employed on the AFOSR apparatus, and on other vacuum systems in the UTK Plasma Science Laboratory. During the summers of 1985, 1986 and 1987, we installed and painted additional cabinets, painted the workbench, constructed additional shelves, and otherwise upgraded the laboratory working environment. Abstracts of some of the apparatus and instrumentation-related meeting papers which were reported during this period of the research are given in Appendix G, pages G-17, G-21, and G-29.

Absolute Measurements of RF Plasma Emissions

During the latter half of 1984 and the first half of 1985, the principal focus of our research activity was the absolute measurement of RF emission power from our Penning discharge plasmas. To accomplish this, we used the

calibrated, broadband antennas described in abstract G-13. These antennae were developed by Mr. Paul Spence, the Senior Research Assistant of the ONR contract, with ONR support. In developing these antennae, Mr. Spence had assistance and advice from Professor David Rosenberg, of the UTK Department of Electrical and Computer Engineering, some of whose time was supported by the AFOSR contract.

These antennae have allowed us to do something which other plasma research groups have been able to do only very approximately if at all; measure the RF emission from a plasma in absolute units of watts per square centimeter in the far field, while receiving the RF emissions over a broad range of frequencies (in our case from 100 MHz to 1.2 GHz) with broadband antennas having a nearly flat frequency response. Thus, when we look at an emission power spectrum from one of our Penning discharges, we can be assured that, over the frequency range just quoted, we are looking at the characteristics of the plasma itself, and not at the frequency response or response pattern of our antenna. Also, when we integrate the total power under the frequency spectrum so observed, we have a reasonable assurance that we are measuring the total power emitted by the plasma. This allowed us to make measurements of emitted power as a function of plasma number density, magnetic field, operating conditions, and, most important for Navy applications, the electrical efficiency in terms of the total RF output power divided by the electrical power required to energize the discharge.

During the academic year 1985-86, the low frequency and microwave network analyzers, and other equipment purchased with the DoD-URIP equipment grant, were put into service and applied to the data taking process

with some very gratifying results, which were presented at the November, 1985 APS Plasma Physics Division meeting (Appendix G, page G-14); and at the IEEE meeting in Saskatoon, Canada, in 1986 (Appendix G, page G-20).

The network analyzers were used to measure absolute RF power in the near and far field of the classical Penning discharge. The emission spectra observed covered the frequency range from 0 to 1 GHz. The measured power has been plotted against the electron number density calculated from Langmuir probe measurements in Figure 12. The efficiency, defined as the radiated RF power, divided by the dc input power to the discharge, was also measured as a function of the input power and is plotted in Figure 13. These efficiency measurements were disappointing. The efficiency of power generation in the frequency band from 0 to 1 GHz was on the order of 0.1%, and tended to decrease with increasing power input to the discharge. The power radiated from the discharge increased no faster than linearly with the electron number density of the discharge. Even at number densities above 4 x 10^9 electrons per cubic centimeter, the radiated power declined with increasing electron number density, perhaps as a result of a self-shielding effect.

During the Summer and Fall of 1985, a series of paired comparison measurements were made on the AFOSR classical Penning discharge, and the modified Penning discharge operated for our ONR contract in the UTK Plasma Science Laboratory. The two Penning discharges were operated over a range of number densities between 1.0 and 10 x 10^9 electrons per cubic centimeter, whil;e the far-field radiation was observed with our calibrated, broadband antennae, which measured the emitted radiation in the bandwidth

Integrated Far Field RF vs Average Electron Number Density

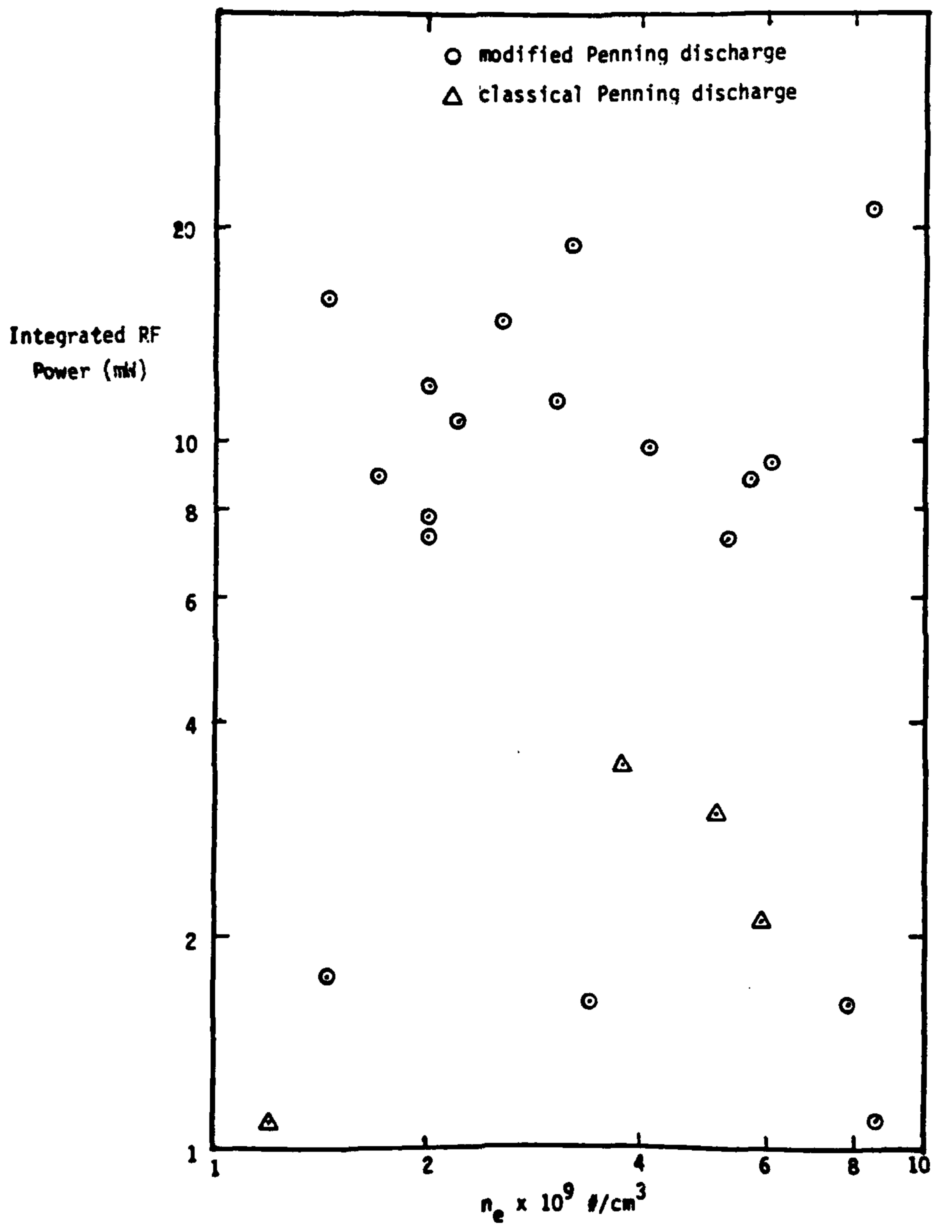


Figure 12

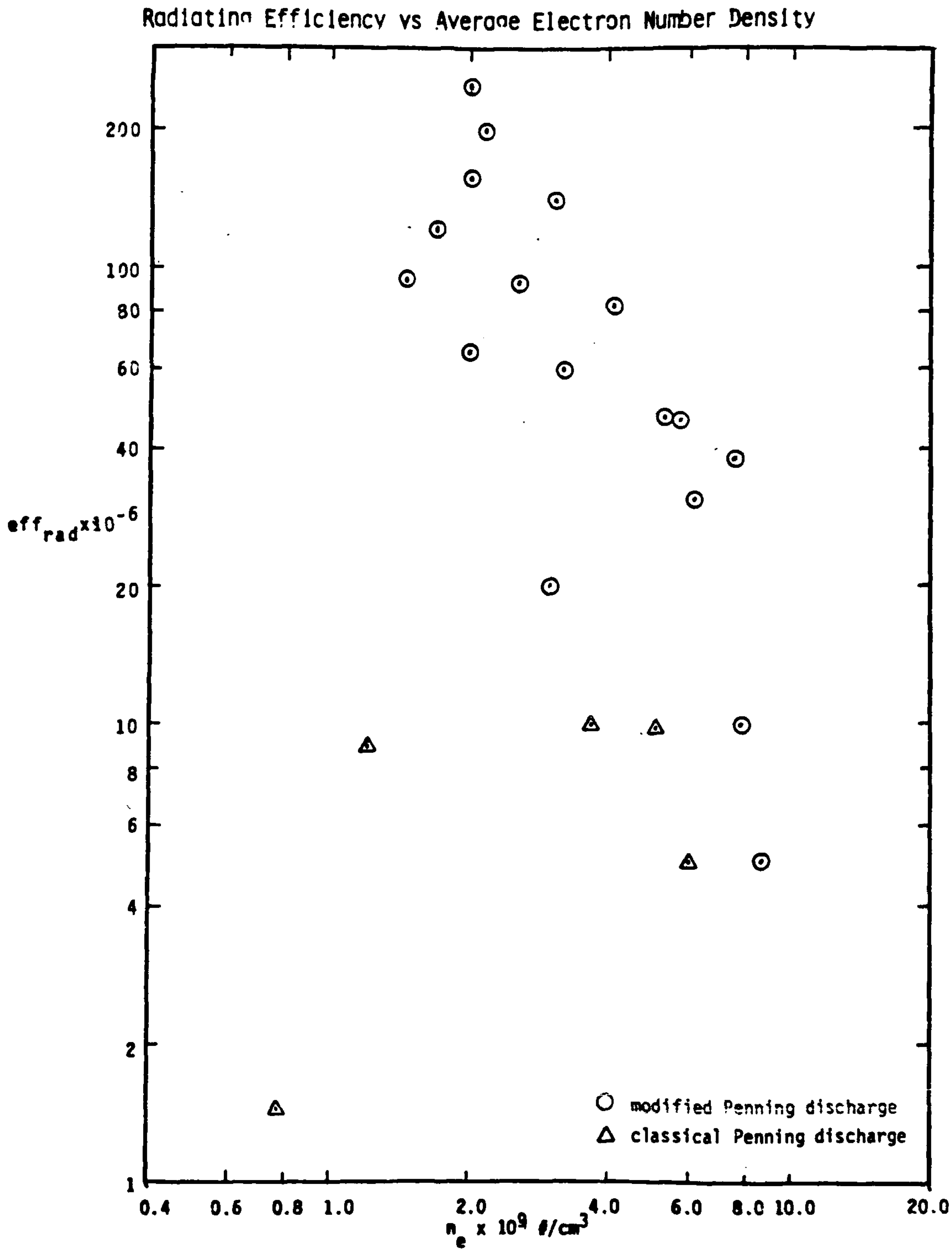

Radiating Efficiency vs Average Electron Number Density
200
100
80
60
40
eff_rad x10^-6
20
10
8
6
4
2
1
modified Penning discharge
classical Penning discharge
0.4
0.6
0.8
1.0
2.0
4.0
6.0
8.0
10.0
20.0
n_e x 10^9 #/cm^3

Figure 13

from 100 to 1000 MHz. It was found that the integrated RF power from the ONR modified Penning discharge, operated in a mirror magnetic field, was at least a factor of five times higher than the RF power emitted from the AFOSR classical Penning discharge. These data are shown in Figure 12. The radiation efficiency is defined as the integrated RF power of an isotropic emitter over 4π steradians, divided by the dc electrical input power to the discharge. This radiation efficiency is plotted as a function of the average electron number density for the classical and modified Penning discharges on Figure 13. here again, it is evident that the modified Penning discharge generates broadband radiation much more efficiently than the classical Penning discharge of the Air Force experiment. The difference in radiation efficiency is characteristically an order of magnitude. The efficiency of the modified Penning discharge decreases with increasing number density, perhaps as a result of a self-shielding effect of the plasma. The magnitude of the radiation efficiencies for this data set are even smaller than earlier data, taken at higher anode voltages. The fraction of the dc input power radiated as RF varies between one part in 10^4, and one part in 10^5. On Figure 14 is shown the radiation efficiency as a function of the effective dc resistance of the discharge. This is obtained by dividing the anode voltage by the anode current, and is related to the anomalous resistivity in the bulk of the plasma.

These data were somewhat discouraging, in that they seem to indicate that the steady state version of the classical Penning discharge is not very efficient in converting dc electrical power into broadband radiation. The data on Figure 12 indicate that the integrated power emitted from the classical Penning discharge is on the order of 1 to 4 milliwatts, when several hundred

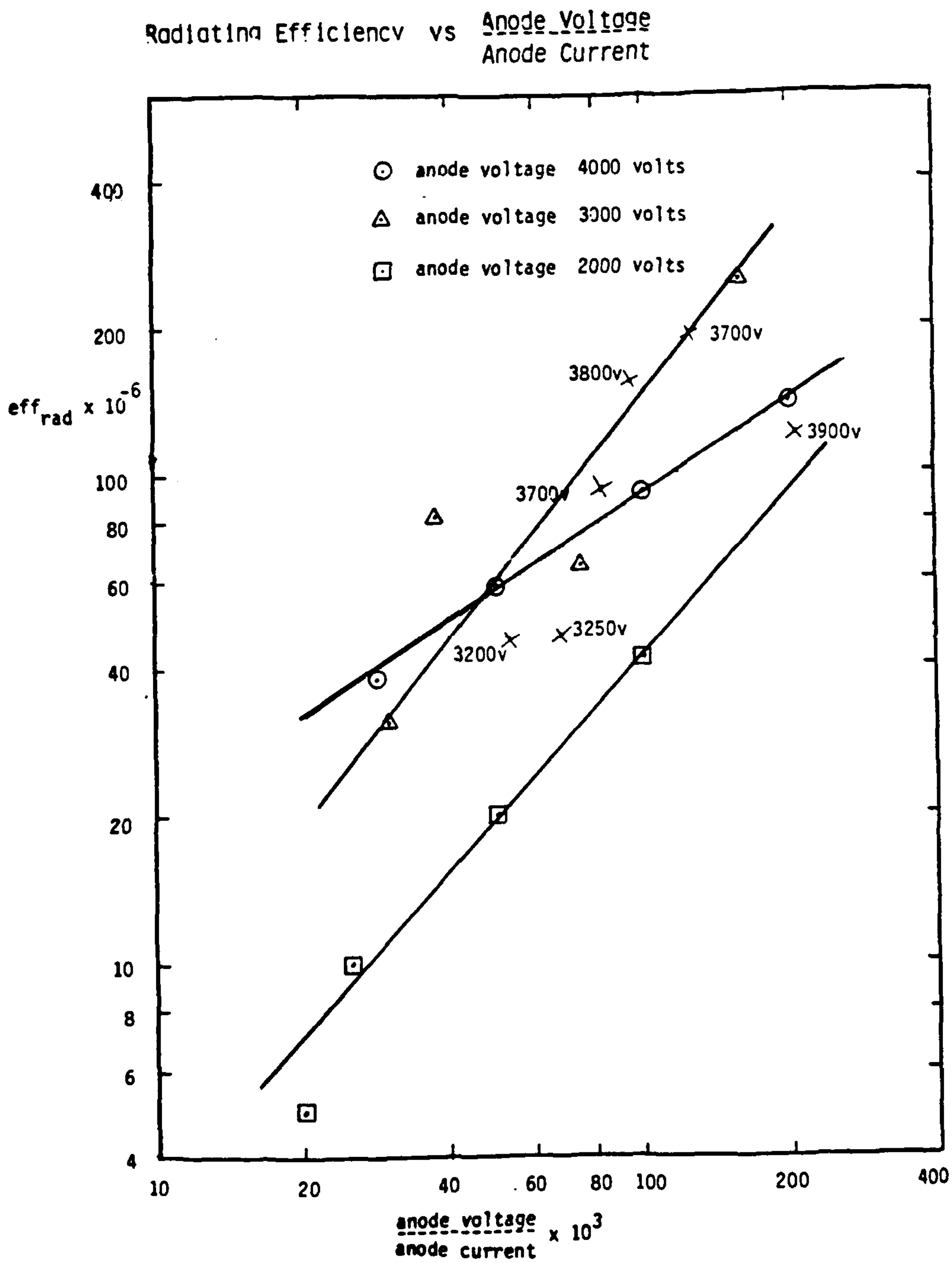

Radiating Efficiency vs Anode Voltage / Anode Current
anode voltage 4000 volts
anode voltage 3000 volts
anode voltage 2000 volts
3700v
3800v
3900v
3700v
3250v
3200v
eff$_{rad}$ x 10^{-6}
400
200
100
80
60
40
20
10
8
6
4
10
20
40
60
80
100
200
400
anode voltage / anode current x 10^3

Figure 14

watts of dc power are consumed by the discharge. These low efficiencies may result from the RF generation mechanism being inherently inefficient, or it may result from relatively large fixed losses in the classical Penning discharge which are necessary to produce the volume ionization to sustain the plasma. If the latter is the case, a pulsed version of the classical Penning discharge, operating at much higher powers, might be much more efficient. However, it appears that the modified Penning discharge, with its axial magnetic field gradients and higher axial electric fields, is a more effective configuration for generating broadband RF power than the classical Penning discharge used in the Air Force experimental program. Abstracts of papers on the absolute RF emission measurements are included for this contract period in Appendix G, pages G-14, and G-18.

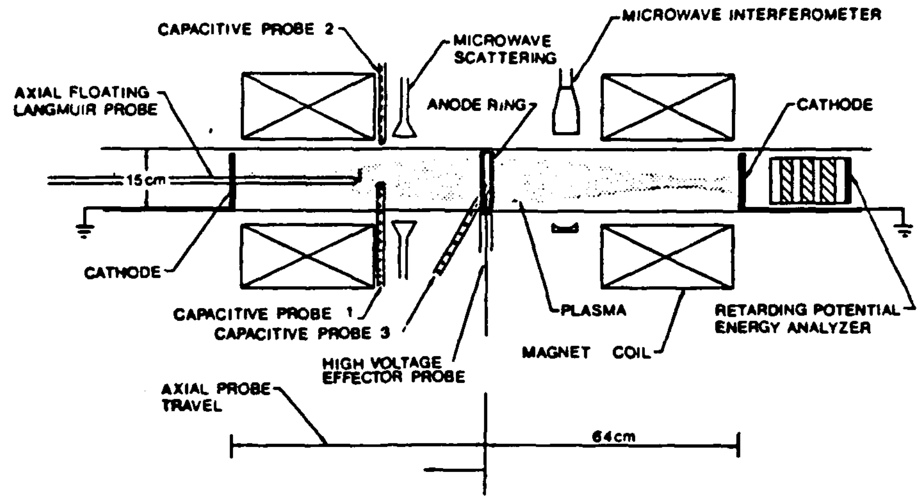
Measurement of Plasma Fluctuations and Turbulence

The edge region of a magnetically confined hot plasma is characterized by large temperature, potential, and density gradients. These gradients drive various nonlinear instabilities resulting in drift waves and broadband edge turbulence. Drift waves in a turbulent plasma are typically quasiperiodic with finite coherence lengths. When externally enhanced, these waves can have increased coherence lengths and exhibit strong mode coupling, with an increase in the number of observed harmonics. Increased background turbulence, electron heating and modification of the spectral index have been observed. Under special conditions, using a subharmonic external signal, drift modes and background turbulence have been damped. Increased electron temperature and number density are observed with damping.

The ONR experimental apparatus in the UTK Plasma Science Laboratory creates a steady state modified Penning discharge capable of electron number densities of up to a few $10^{10}/cm^3$, at electron temperatures of 10 to 100 eV. The 60 cm long discharge consists of an anode ring and two cathode end plates (see Fig 15). The confining magnetic field has a 5.1 to 1 mirror ratio with the maximum field variable up to 0.33 Tesla. A glass vacuum vessel surrounds the discharge and allows external detection of the electrostatic fluctuations associated with the turbulence and drift waves on the edge of the plasma. The base pressure of the system is typically 6 microtorr, with operating pressures up to 100 microtorr. Helium gas was used for the data discussed.

At the midplane of the discharge, a tungsten probe is inserted radially thru the anode ring, shown schematically in Figure 16. This "effector probe" is DC biaed to the anode potential and is AC coupled to either a full sine wave or a positive half rectified sine wave. A Ling power amplifier capable of up to 1.0 amp at 5 kilovolts over the frequency range 0.5 to 100 kHz is used to drive the effector probe for turbulence enhancement and damping studies. Input power from the probe to the plasma is typically 5% to 15% of the DC input power.

Electrostatic fluctuations at the plasma edge are detected using capacitive probes located on the glass vacuum vessel. Detected signals in the frequency range 0.01 to 2 MHz are amplified and viewed on a spectrum analyzer, a network analyzer, or digitally sampled using our LeCroy 3500 signal processing system. Under conditions having a high degree of coherence, the H.P. network analyzer yields the phase information between



MODIFIED PENNING DISCHAGE
(TOP VIEW)

Figure 15

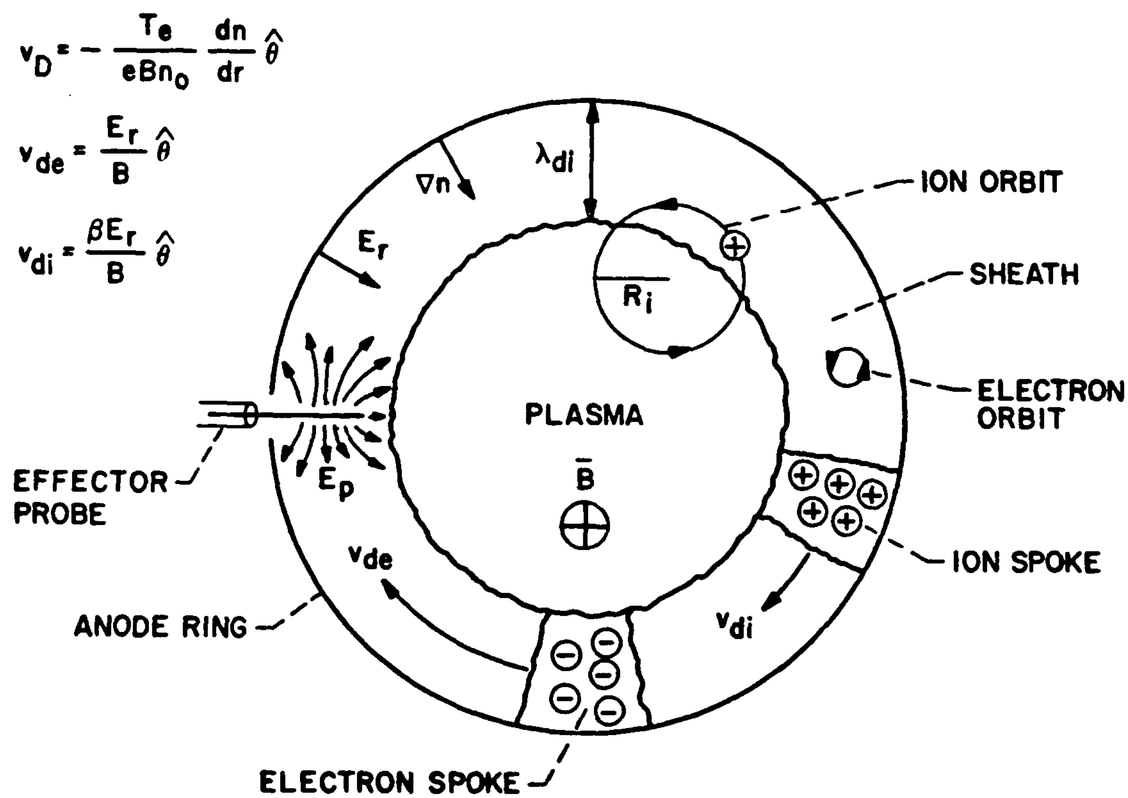


Figure 16

two probes. This phase information can be related to the direction and velocities of wave propagation. Digital time series analysis of the transient samples of these signals is also performed to yield auto and cross power spectra, and phase and coherency spectra.

A cross sectional view of the plasma at the anode is shown in Figure 16. Both the radial electric field (due to the anode) and a density gradient will cause the plasma to rotate azimuthally. These drifts can oppose or complement one another depending on the sign of the gradients. Finite gyroradius effects will enhance a departure from quasineutrality in the sheath region of the plasma. Charge clumps will form as a result of the diocotron instability, from a local perturbation of the radial electric field (or density gradient). Ion and/or electron spokes will propagate azimuthally, producing periodic potential variations for detection by a stationary capacitive probe.

The effector probe consists of a tungsten filament inserted radially at the anode. This probe was intended to couple to and drive an existing E x B spoke. This probe generates axial and azimuthal electric field components, as well as a radial component. Coupling to a ∇n drift wave is assumed to be through the modification of the potential ϕ in a Boltzmann distribution, where

$$n(r) = n_0(r)\exp\left(\frac{e\Phi}{T_t}\right) \approx n_0(r)\left(1 + \frac{e\Phi}{T_e}\right) \tag{5}$$

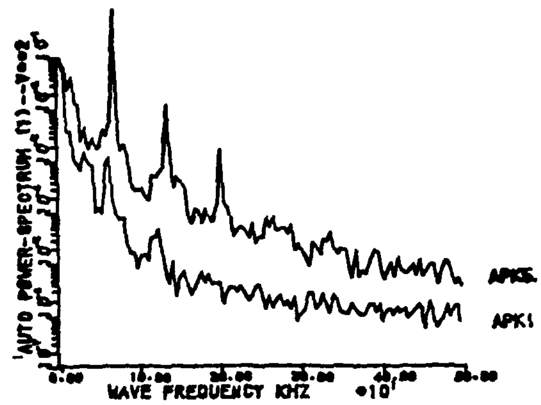
Auto power spectra for typical plasma conditions with and without external excitation are shown in Figure 17. The self excited spectrum (APK1) was taken on probe 1 with an anode voltage of 4400 volts and current of 38

mA. The enhanced spectrum is taken while a 68 kHz, 1 kV, 5 mA half wave rectified signal is applied to the effector probe. The enhanced spectrum is as much as 20 dB above the self excited level. Highly nonlinear mode coupling is exhibited here due to the continuous "filling" of the spectrum. Note that energy is cascading both upward and downward in frequency space.

Load pulling is an additional feature exhibited with the enhancement of a self excited mode by a signal on the effector probe. The external oscillator can pull the self excited mode frequency as much as 50%. Greater detuning results in decoupling of the probe from the self excited mode and loss of the enhanced spectra.

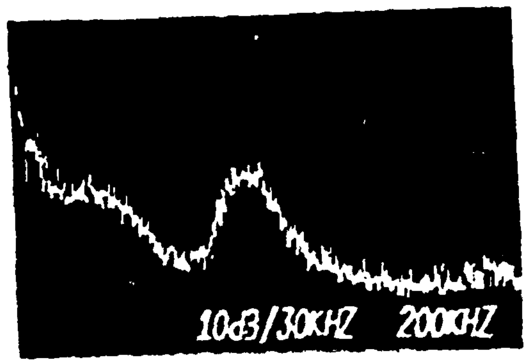
Figures 18 and 19 show the effect of using a low frequency (3.4 KHz, 4 kV_{pp}, 5 mA full sine wave) to damp a high frequency mode. Electron heating and increased number density were observed with damping. Although the high frequency mode is clearly damped in Figure 19, some enhancement at low frequencies is evident. The damping effect is extremely critical in terms of the amplitude and frequency of the effector signal. Variation in frequency of a few percent will produce an enhanced spectrum. The signal amplitude had been carefully adjusted to yield optimum damping for Figure 19.

The electrostatic signal detected from the edge turbulence on a Penning discharge indicates a wide range of phenomena, from quasiperiodic to fully turbulent. The addition of an effector probe to the discharge allows the plasma to be perturbed by a choerent signal resulting in enhancement or damping. The energy cascade mechanism under a controlled perturbation can then be studied under a variety of plasma conditions.



Auto power spectra of electrostatic potential fluctuations from 0 to 500 kHz. Run APK1, self-excited modes. RUN APK-5 enhanced spectrum with signal on effector probe.

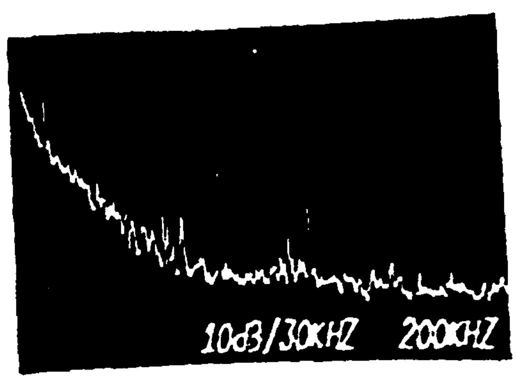
Figure 17



linear frequency scale

Self-excited modes in the plasma over the range 0-2.0 MHz.

Figure 18



Same plasma conditions as Figure 4, with mode damping resulting from a 3.4 kHz signal on the effector probe.

Figure 19

The damping of self excited oscillations by external forcing is discussed in systems with one and two degrees of freedom by V. Migulin, and N. Minorsky. Systems with cubic or quadratic nonlinear dissipation terms can have jumps in amplitude of the self excited mode under external excitation. This suggests the presence of a nonlinear dissipation mechanism in this experiment, where similar phenomena have been observed. Abstracts of conference papers on edge turbulence and the enhancement and damping of turbulent modes during this period of the program may be found in Appendix G, pages G-14, G-15, and G-16.

Measurement of the Anomalous Collision Frequency

A third major research effort on the ONR experimental apparatus was the measurement of the effective electron momentum collision frequency, by using the full width at half maximum of the electron cyclotron resonance absorption curve. Electron cyclotron resonance absorption measurements were made on a weakly ionized, steady-state, turbulence plasma using a Hewlett Packard 8510 network analyzer. This instrument is capable of swept frequency measurements of reflection and transmission coefficients from 0.045 to 18 GHz, with greater than 80dB dynamic range. The absorption measurements near electron cyclotron resonance are interpreted in terms of numerical solutions of the Appleton equation to yield an "effective" collision frequency equal to the full width of the absorption curve at twice the resonance minimum. A two channel homodyne microwave scattering system (f_o = 14 GHz) is used along with a capacitive probe to measure turbulence levels. Axial and radial Langmuir probes are used for electron number density and kinetic temperature measurements.

The ONR apparatus was re-arranged from a 5:1 magnetic mirror to a classical uniform magnetic field configuration. The classical Penning discharge used to generate the plasma (see Figure 20) consists of a uniform magnetic field with a maximum value of 0.195 Tesla. The field is uniform to within 3% between anodes. An approximately 12 cm diameter steady state plasma column is generated which is 118 cm long. This plasma had a characteristic density of a few times 10^9 electrons/cm^3, electron kinetic temperatures 10 eV to 100 eV, and helium ion kinetic temperatures of several hundred eV.

Signals from the capacitive probe and the microwave scattering system were amplified and bandpass filtered. Both signals were processed by a Tektronix 7L5 spectrum analyzer. The turbulence spectrum power levels are measured using a Boonton model 91-12F RF detector. High pass filtering is 100kHz with low pass at 2 MHz. The apparatus was adjusted to try to maintain signal (power) levels at least 10 dB above the noise levels. The antenna geometry for the electron cyclotron resonance absorption measurements made on this plasma is shown in Figure 21, and the actual hardware on Figure 22.

Figures 23 and 24 show a characteristic resonant absorption curve on the top, and the phase angle on the bottom. The sweep time for these traces is 500 msec with 10 traces averaged. It is desired that an electron remain in the beam sufficiently long to damp the absorbed energy by collisions rather than transport it out of the beam region by axial motion at the thermal velocity. For all data reported here, the product $\tau_e\, v_{eff} > 1$, implying that electrons made at least one collision while they were in the microwave probing beam. This is

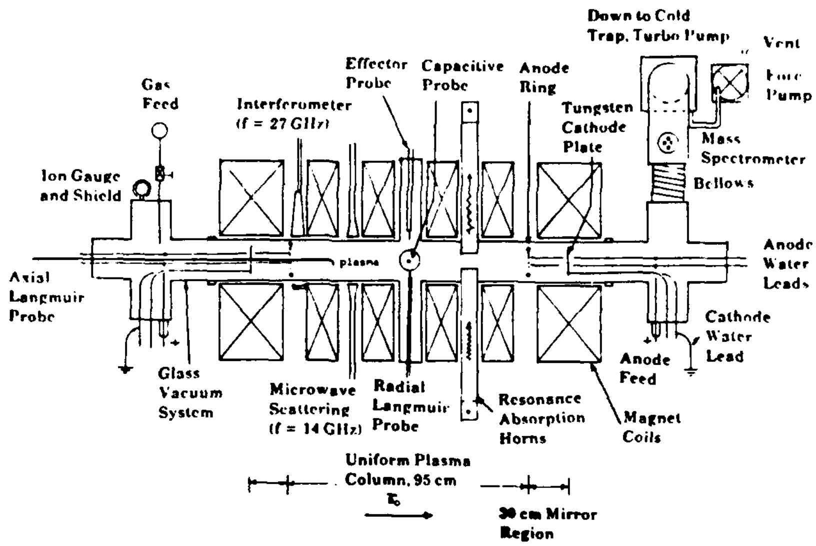


Figure 20

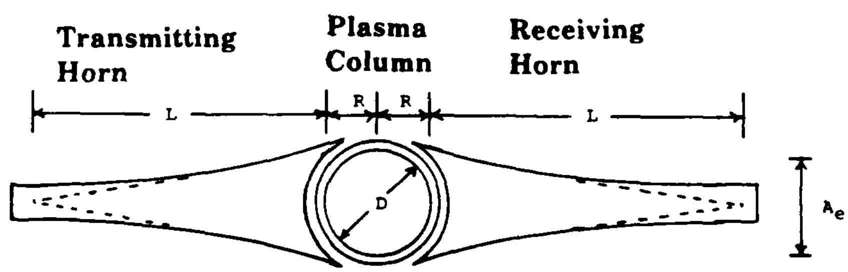


Figure 21

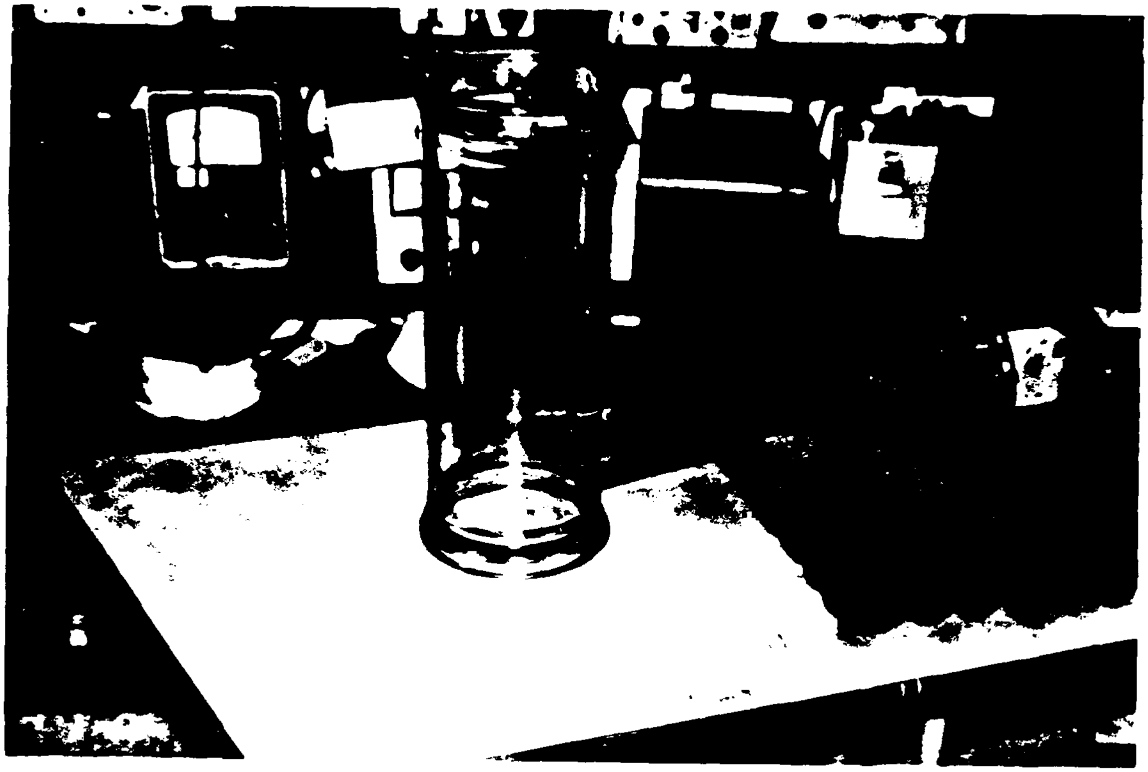


Figure 22

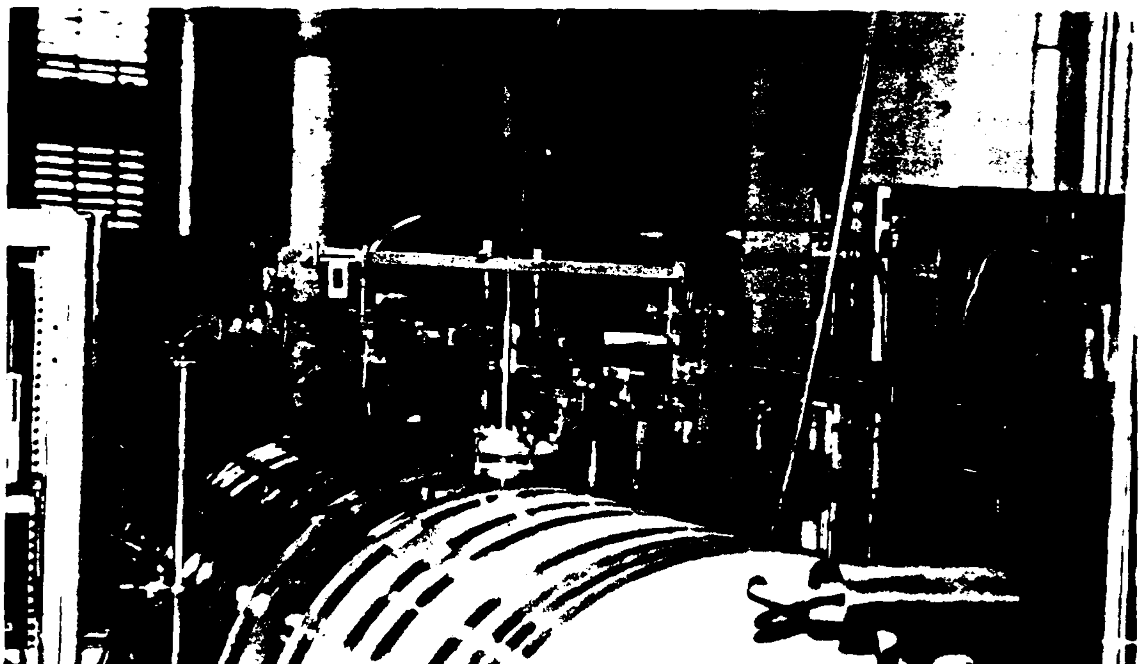


Figure 27

Attenuation, dB

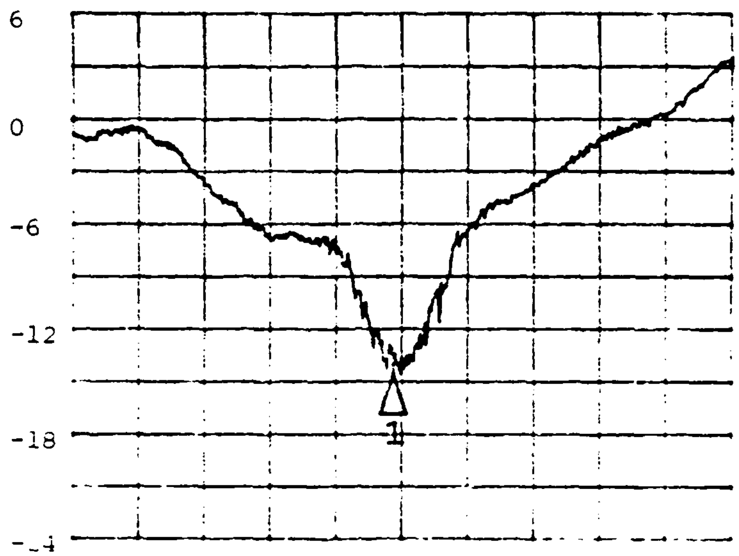
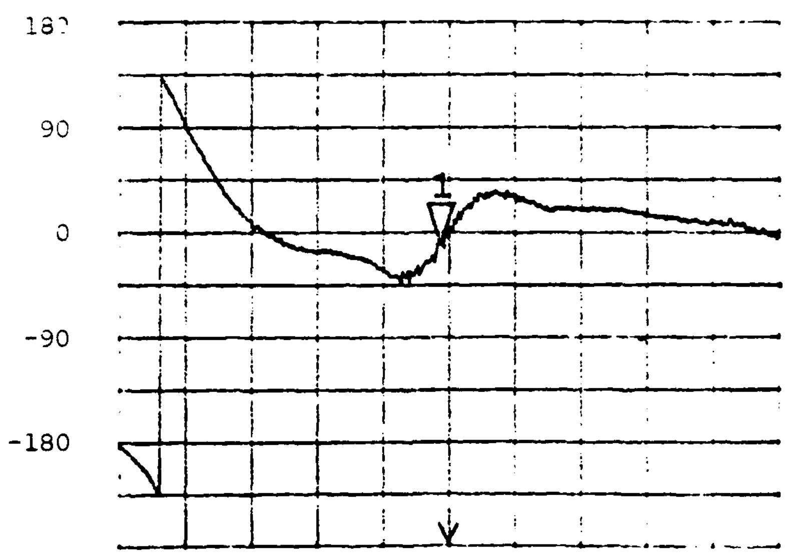


Figure 23a

Phase Angle, Degrees



Center Frequency 2.6954 GHz

0.50 GHz Per Division

Figure 23b

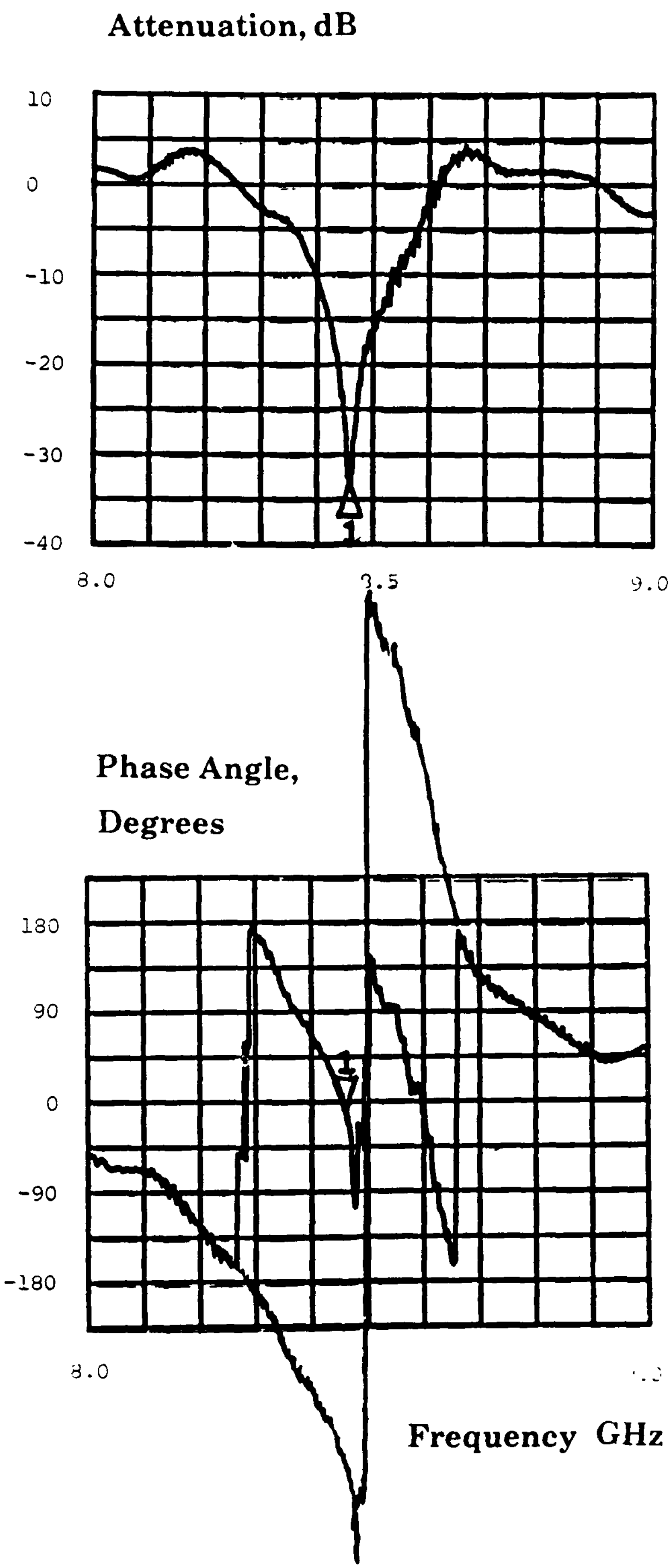
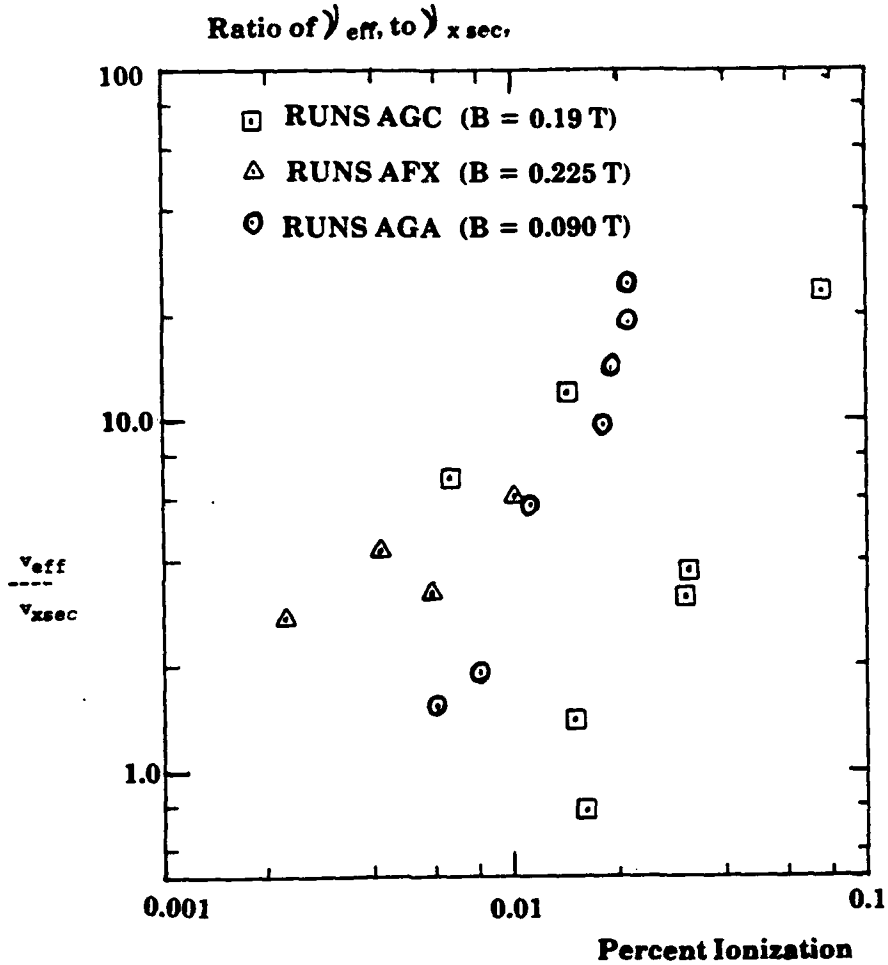


Figure 24a and 24b



Ratio of ν eff, to ν x sec,
100
10.0
1.0
RUNS AGC (B = 0.19 T)
RUNS AFX (B = 0.225 T)
RUNS AGA (B = 0.090 T)
veff
----
vxsec
0.001
0.01
0.1
Percent Ionization

Figure 25

demonstrated in Figure 25. The Appleton equation is a hydromagnetic equation relating a Lorentz collision term in a cold plasma to the propagation constants of an electromagnetic wave. Numerical solutions to it were obtained for characteristic plasma conditions such as Figure 23 and 24; in general, it was found that the numerical solution had a resonance curve much narrower than the experimental data, and that the data often exhibit secondary absorption peaks or "plateaus" (like Figure 23) which were not predicted by the Appleton equation. This may be a non-linear mode coupling or a hot plasma effect.

Galeev and Sagadeev introduce an effective collision fequency based on Langmuir turbulence (no magnetic field present);

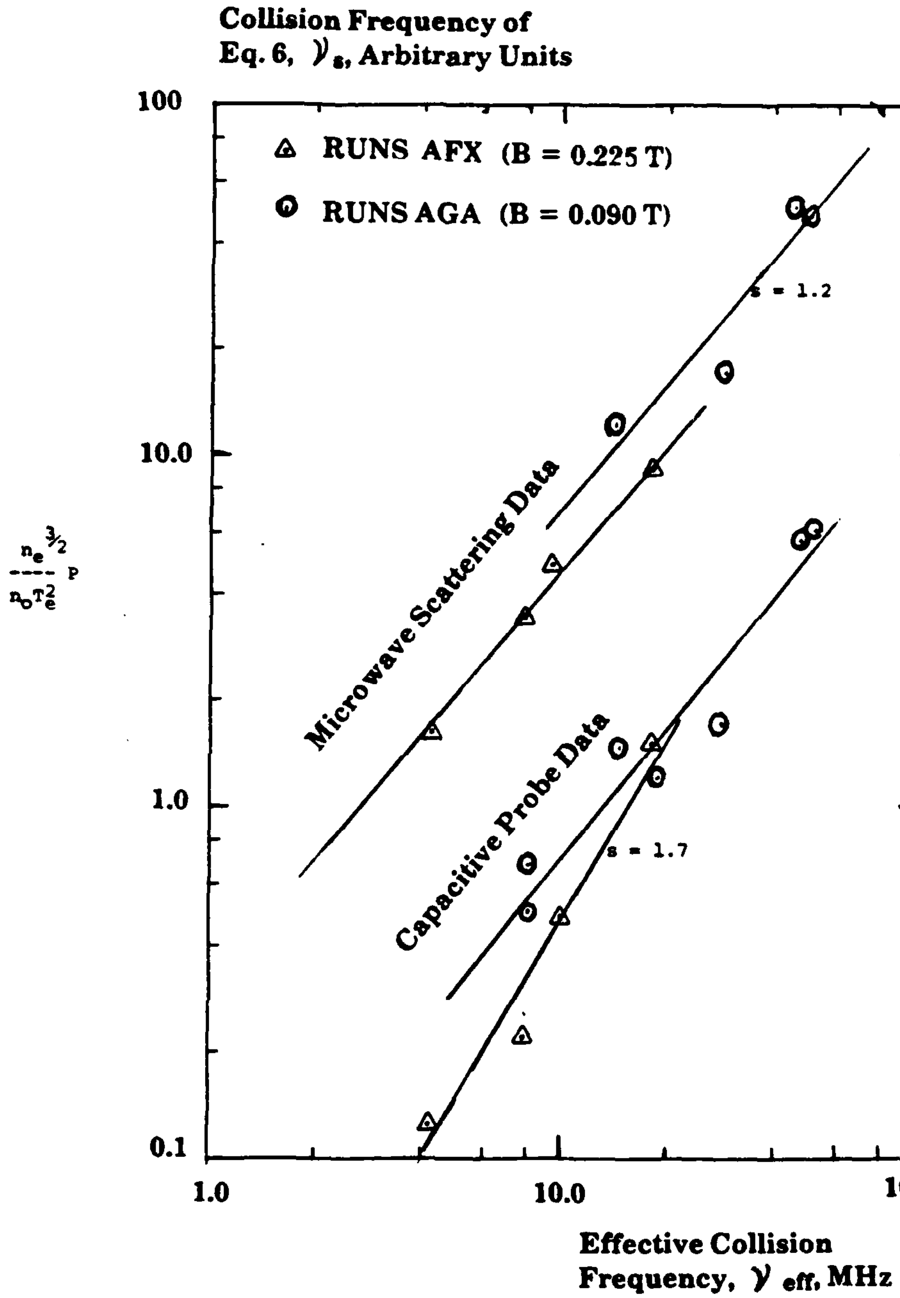
$$v_s \omega = \omega_{pe} \frac{W}{n_o T_e}, \tag{6}$$

where W is the energy density of waves in the region of interest with wavelengths on the order of the Debye radius.

For drift wave turbulence, W. Horton derives the total fluctuation energy density

$$W = \sum_k W(k) = \frac{e^2 n_e}{2T_e} \int dk \left[\phi(k)^2 + \left(\nabla_\perp \phi(k) \right)^2 \right] \tag{7}$$

The capacitive probe will measure a function of $\phi(k)$ with the scattering power related to $\nabla_\perp \phi(k)$. Since neither the capactive probe nor the microwave scattering are absolutely calibrated, v_s is plotted in Figure 26 as a function of



Collision Frequency of
Eq. 6, ν_s, Arbitrary Units
RUNS AFX (B = 0.225 T)
RUNS AGA (B = 0.090 T)
s = 1.2
s = 1.7
Microwave Scattering Data
Capacitive Probe Data
$\frac{n_e^{3/2}}{n_o T_e^2} P$
100
10.0
1.0
0.1
1.0
10.0
100
Effective Collision
Frequency, ν_{eff}, MHz

Figure 26

$$v_s \sim \frac{n_e^{3/2}}{n_0 T_e^2} P, \qquad (8)$$

where P is the integrated power spectra for either the capacitive probe spectra or the microwave scattering spectra, and n_0 is the neutral background density. Figure 27 shows the microwave scattering apparatus used. Figure 26 indicates a disagreement of our data (v_{eff}) with the theory of Galeev and Sagadeev as elaborated by Horton (v_s), since the data do not lie along a straight line with a 45° slope, which would indicate a linear proportionality.

The measured effective collision frequency was consistently larger than the calculated electron-neutral collisional values, using the cross section for the latter at 10 eV. The effective collision frequency is as much as 20 times binary, Lorentzian value. This increase in collision frequency is very probably due to electron scattering by plasma turbulence.

The use of a hydromagnetic equation avoids any Landau damping effects. However, two minima have been observed in the resonant absorption curves, indicating possible hot plasma effects (see Figure 23). The broad resonance curve and large phase shifts, as well as the double minima, indicate that a hydromagnetic treatment is not sufficient, although it does provide a good first approximation.

Abstracts of papers on the effective collision frequency measurement presented during this contract period are included in Appendix G, pages G-20, G-22, and G-23.

Research on Interpenetrating Beam Instability

During 1985, Prof. Igor Alexeff and I continued our collaboration on the theory of growing waves and electromagnetic emission from two oppositely directed electron beams in a cold background plasma. This collaborative work has extended our discovery papers on the interpenetrating beam or geometric mean emission frequency, which were written up in reference D-1 of Appendix D. We presented a paper on our theoretical results at the 26th Annual Meeting of the APS Division of Plasma Physics, which was held in Boston, Massachusetts from October 29 through November 2, 1984. This abstract is included in Appendix G, page G-30.

In that paper, we presented a generalization of previous theoretical work to the case of two nonrelativistic, oppositely directed interpenetrating electron beams of unequal density, interacting with a cold background plasma. These conditions can be reduced to a sixth order cold plasma dispersion relation with growing and damped solutions. In the case of two beams, each half of the total electron density, interacting with cold ions, we recovered our previous result, quoted in reference D-1. The previous results predicted growing waves near the geometric mean of the electron and ion plasma frequency. When the beams are much less dense than the cold electron background density, the growing waves are near the electron plasma frequency of the cold electron population. The maximum growth rate was found to be not at the beam electron plasma frequency or at the upper or lower hybrid frequency. The frequency of an oscillator based on this instability may be tuned by adjusting the relative intensity of the two beams as well as the beam density relative to the background plasma density.

Accomplishments of the FY 1988-March 31, 1989 Research Program

The final contract period of this 9.25 year research program was the 1.5 year contract which funded fiscal year 1988, and was extended at no cost to the Navy for six months to March 31, 1989. The final six month extension was granted to complete experimental work on the nonlinear dynamics and chaos investigation; to write up a Master's thesis on the nonlinear dynamics research, to finish writing up a Ph.D. thesis on the effective collision frequency and active modification of plasma turbulence; to write this final report; and finally to provide time for an orderly transfer of the surplus DoD equipment obtained under our ONR contract, to the University of Tennessee where it will be used for other plasma related programs.

Apparatus Modifications

During this period of the research program, the vacuum system was rebuilt to allow axial access to the plasma from either end of the coil system, rather than having one end blocked by the vacuum pump; a long, axisymmetric anode cylinder was installed, to provide better control over drift modes which were observed at the edge of the plasma; a microwave scattering system was installed to measure the level of density fluctuations in the plasma; and an effector probe, biased at the anode potential and capable of a high voltage ac bias about the anode potential, was installed for the active turbulence modification experiments; new Langmuir and capacitive probes were built and installed; and the diagnostic systems refined and calibrated for

measurement of the absolute levels of plasma potential and density fluctuations.

No modifications beyond those described above were necessary for the experimental runs taken to study the nonlinear dynamics of plasma turbulence using chaos theory. Experimental work for the Navy contract ended in mid-December, 1988, and the apparatus is now being used as a temporary test bed for plasma ion implantation experiments. These materials science plasma processing experiments are being done for the Army Research Office. If the ARO work on plasma ion implantation is funded beyond June, 1989, we expect the ONR apparatus to become available once again for basic plasma physics experimentation, and we also expect to build an entirely new apparatus for the plasma ion implantation experiments.

Measurement of Anomalous Collision Frequency

As part of the Ph.D. thesis of Paul D. Spence, measurements were taken of the resonant absorption peak for microwave energy at the electron cyclotron frequency, using our HP model 8510 microwave network analyzer. An extensive series of runs were taken of this resonant peak, from which it was possible to determine the effective electron collision frequency in the plasma. In this most recent and sophisticated series of measurements, we did not use the approximation that the effective electron collision frequency was equal to the full width at half maximum of this electron cyclotron absorption peak. The actual shape of the electron cyclotron resonant absorption peak was calculated from the Appleton equation, and the effective electron collision frequency was related to the electron cyclotron frequency and the electron

plasma frequency. This more sophisticated approach to relating the effective electron collision frequency to the shape of the electron cyclotron absorption peak did not produce large numerical factors of difference with the effective electron collision frequencies previously reported, but did provide a more accurate value for comparison with theories of the effective electron collision fequency in turbulent plasmas put forward by Galeev and Sagadeev, as refined by W. Horton.

At the same time that we refined the interpretation of the electron cyclotron resonant absorption peak, Mr. Spence also took simultaneous data on the level of electrostatic potential fluctuations in the plasma with a capacitive probe, and of electron density fluctuations using microwave scattering. These latter two diagnostics produced absolute values of potential and density fluctuations in the plasma, which allowed a quantitative as well as qualitative comparison with the theories of the individuals named above. In general terms, it was found that the effective collision frequency experimentally measured by our new diagnostic technique agreed very well with the theory of Galeev and Sagadeev, both in terms of the functional dependence of this collision frequency on plasma parameters, and in the absolute magnitude of the effective collision frequency which we observed. In this highly turbulent plasma (an excellent test bed for this type of investigation), the effective collision frequency of the electrons was often a factor of 10 or more higher than the largest binary collision frequency in this plasma, that between electrons and neutral background atoms. It is expected that this work on the effective collision frequency will be written up not only in Paul D. Spence's thesis (Paul expects to graduate in August, 1989), but also

in archival journal articles describing his work. Some of this more recent work on the effective collision frequency was written up for a paper at the IEEE meeting in Seattle, in June, 1988. An abstract of this paper may be found in Appendix G, on page G-27.

Measurements of Active Modification of Plasma Turbulence

The work of previous years indicated that a great deal of information about nonlinear mode coupling could be obtained by examining the auto power spectrum of density and potential fluctuations in the plasma, while the plasma was being excited by an effector probe. The most effective coupling of the signal imposed on the effector probe to the plasma turbulent spectrum appeared to occur when the effector probe was biased to the DC potential of the Penning anode ring, and was in contact only with the edge of the plasma in the sheath between the anode cylinder and the plasma itself.

During FY 1988, an extensive series of measurements were taken, sometimes under the same conditions for which the effective collision frequency was being measured, and a wide variety of nonlinear mode coupling phenomena were observed. We observed an energy input into the turbulent spectrum of the plasma, the energy being fed in by the signal on the effector probe. Under such conditions, we commonly observe an enhancement of the turbulence in the plasma due to external excitation of the effector probe. The character of the mode coupling between the frequency imposed on the effector probe, and the drift modes at the edge of the plasma, changed as the frequency on the effector probe was changed. Under a few conditions of operation, it was found that a very low frequency signal (about 2 kilohertz) would damp out the

turbulent spectrum, and reduce the overall energy level in the turbulent spectrum by as much as 10 to 20 dB. This rather surprising observation was examined further, and more extensive diagnostic measurements were taken under conditions when this was observed to take place.

Experimental work on the active modification of plasma turbulence ended in the early Summer of 1988. These experimental results have been written up for plasma meetings, abstracts of which are included in Appendix G, on pages G-25 and G-26. This work is also being written up as part of Paul D. Spence's Ph.D. thesis, and it is expected to be included in one or more archival journal articles to be based on his thesis research.

Nonlinear Dynamics and Chaos in Plasmas

Previous experiments on the classical Penning discharge configuration of our ONR apparatus (that with an approximately uniform axial magnetic field) have shown the existence of drift instabilities at the plasma edge. By using a long, cylindrical anode and applying a signal on the effector probe, relatively coherent modes have been observed. The nonlinear dynamics of these modes were studied. Capacitive probes are used to measure potential fluctuations. These signals are digitized and then processed with software obtained from Dynamical Systems Inc. This software will reconstruct the phase portraits, take Poincare sections, compute correlation dimensions, and compute Lyapunov exponents. The goal of this experimental work was to obtain coherent modes in the plasma; to study the effects of varying the plasma parameters; and finally to determine whether low dimensional chaos is occuring.

For this series of experiments, the classical Penning discharge was operated in the steady state. Under normal operating conditions, with an anode ring and cathode plates, the plasma is at a high level of turbulence. For this experiment, a long, cylindrical anode is used with a coaxial cathode; cathode plates are also used at the end of the axially uniform region of magnetic field. This arrangement produces a constant radial electric field along the axis. This, in turn, creates a strong E/B instability at the outer edge of the plasma. A radial capacitive probe was used to measure the potential fluctuations in the edge region. These fluctuations are digitized and recorded as a time series with LeCroy analog to digital converters. The digitized data was then transferred to our IBM-AT computer on which the digitized data was reduced using the commercial software package obtained from Dynamical Systems, Inc. This investigation was a Master's thesis for Mr. Scott A. Stafford. The main goal of this experiment was to look for evidence of low dimensional chaos in the fluctuating signals produced by electrostatic turbulence in this plasma. Also, conditions have been set up in this experiment in such a manner as to produce relatively coherent modes in the plasma, and then several plasma parameters were varied in order to study the transition to full scale turbulence. Three different cases were looked at in this manner; varying the anode voltage, varying the background neutral gas pressure, and varying the magnetic field strength in the plasma containment volume.

A diagram of the experimental apparatus for these investigations is shown in Figure 28. The magnetic field strength along the axis is shown in Figure 29. The data handling system is shown in Figure 30. A particularly

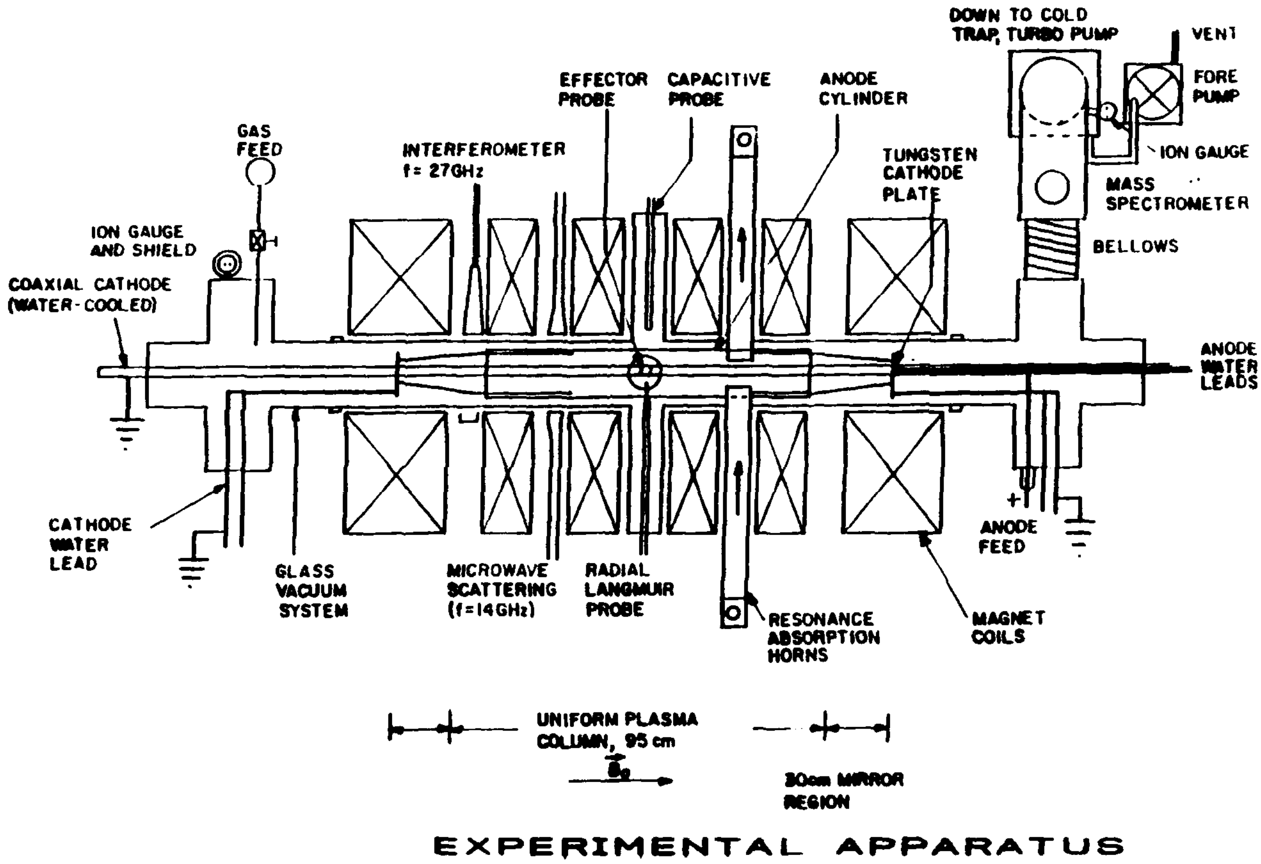


Figure 28

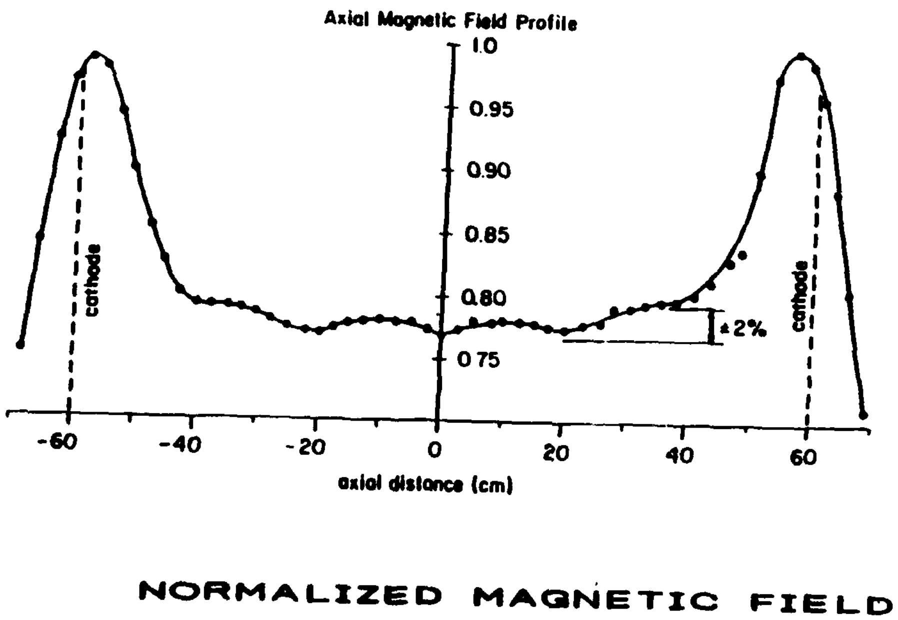
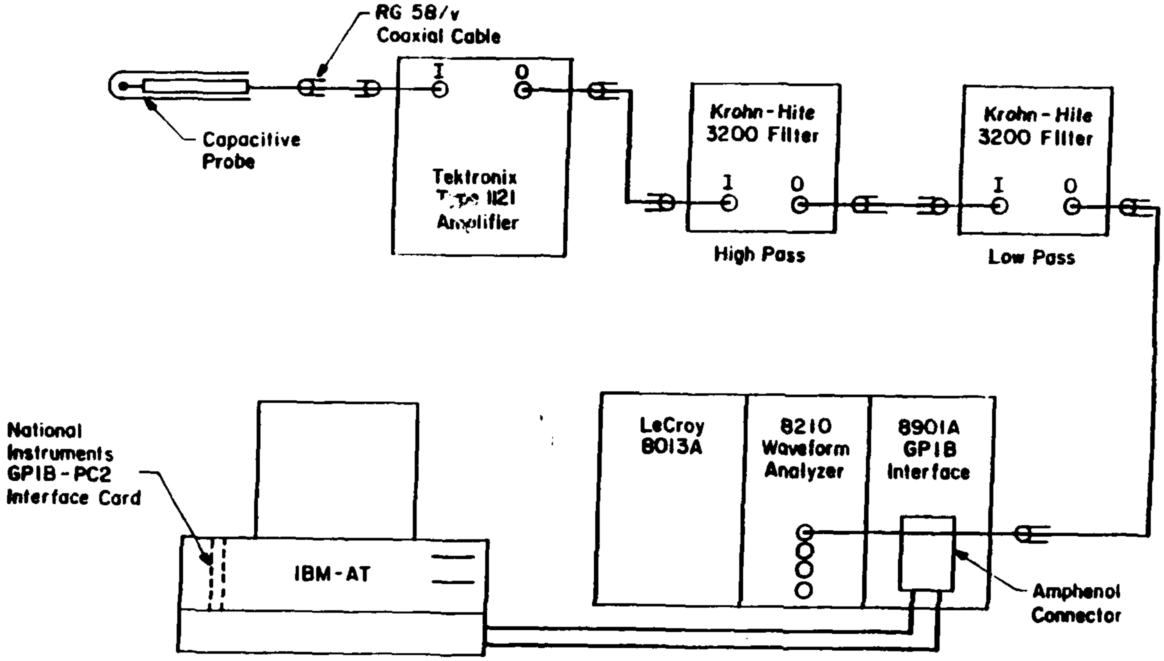


Figure 29



BLOCK DIAGRAM OF DATA ACQUISITION SYSTEM

Figure 30

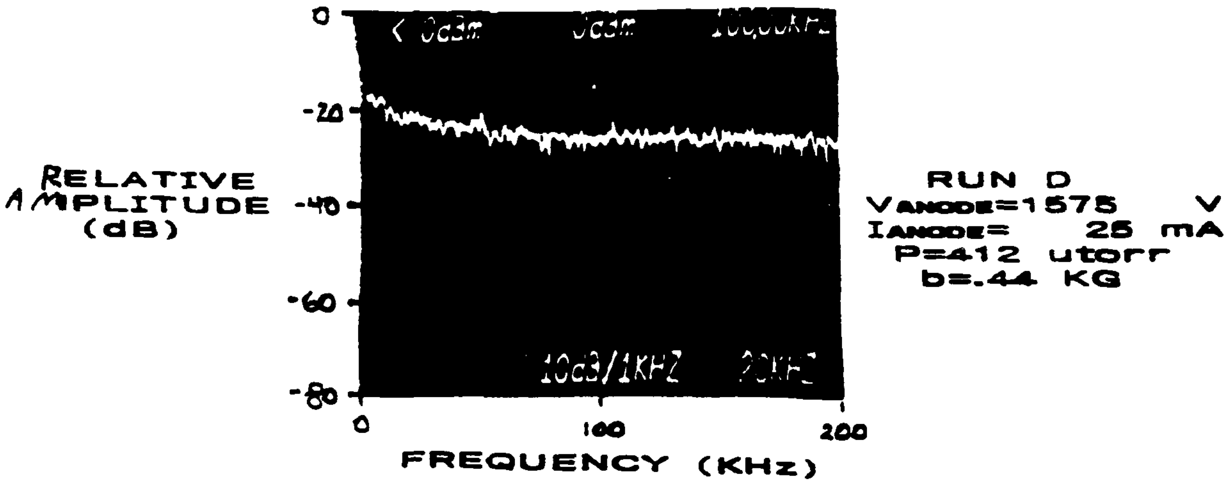
random case of turbulence is shown in Figure 31. Above is the auto power spectrum from 0 to 200 kilohertz, showing a relatively flat, turbulent spectrum with no dominant peaks. The reconstructed phase spectrum shown at the bottom indicates no limit cycle or attractor to the phase trajectory of the fluctuations in this plasma, Figure 32 shows the correlation dimension for this highly turbulent case. A more coherent case is shown in Figure 33, accompanied by the respective reconstructed phase portraits on Figures 34 and 35. Here, a better defined limit cycle, particularly in Figure 35, is apparent. Analysis of these data still continues as of this writing.

This work on the application of nonlinear dynamics to plasma turbulence was reported at the APS meeting in November, 1988. An abstract of this presentation is in Appendix G, on page G-28. A paper reporting completed work on Mr. Stafford's Master's thesis will be presented at the IEEE meeting in Buffalo, NY, in May, 1989. An abstract of this paper is also in Appendix G, on page G-31. Final analysis of this work on nonlinear dynamics and the application of chaos theory to plasma fluctuations is not complete at this writing, but it already appears that this may be a long sought mechanism to get a theoretical handle on the very nonlinear phenonemon which is plasma turbulence.

Miscellaneous Technical Accomplishments

The above sections of this chapter give an account of the research program supported by ONR over the 9.25 period covered by this report. The topics discussed in those sections are the "mainline" research topics on which probably 95% of our time and energy were focussed, and which we originally proposed to do before undertaking the work. Because we are a basic research

RUN D
CASE WITH FULL-SCALE TURBULENCE



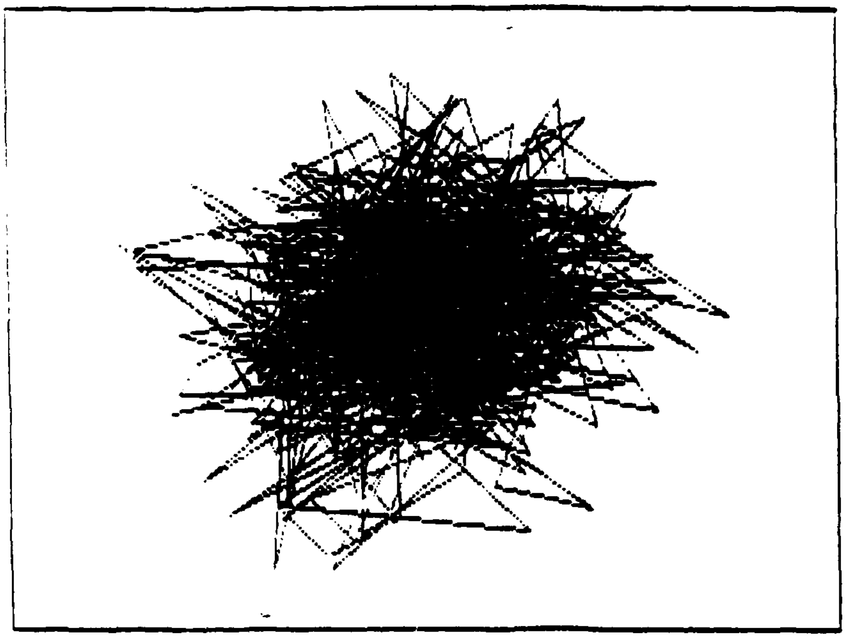


Figure 31

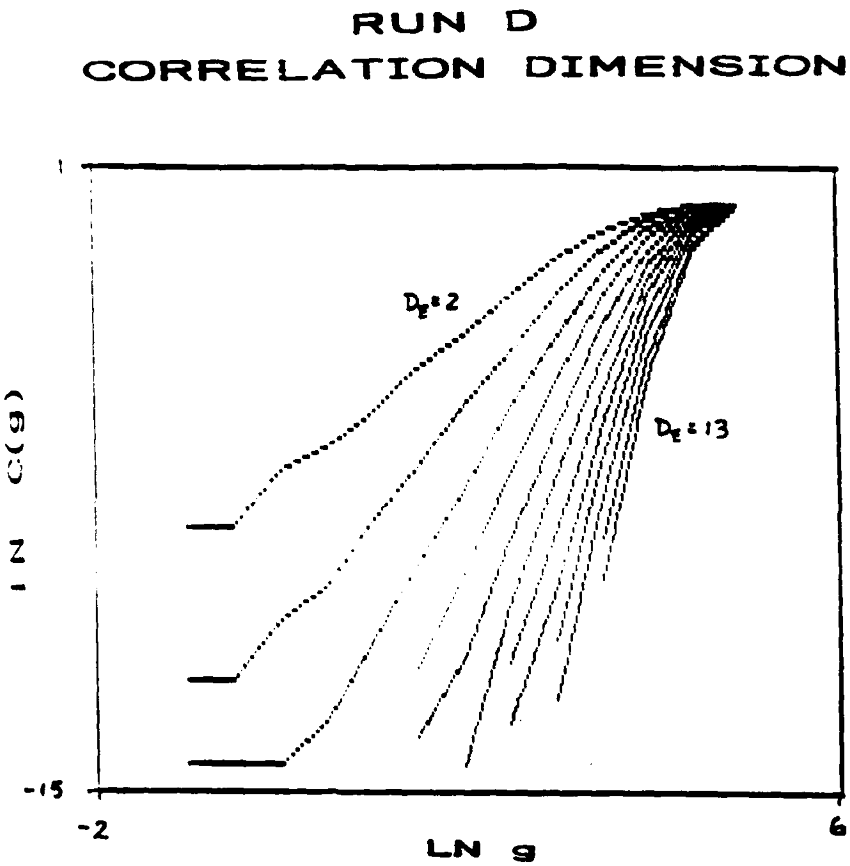


Figure 32

POTENTIAL FLUCTUATIONS FOR DIFFERENT RUNS

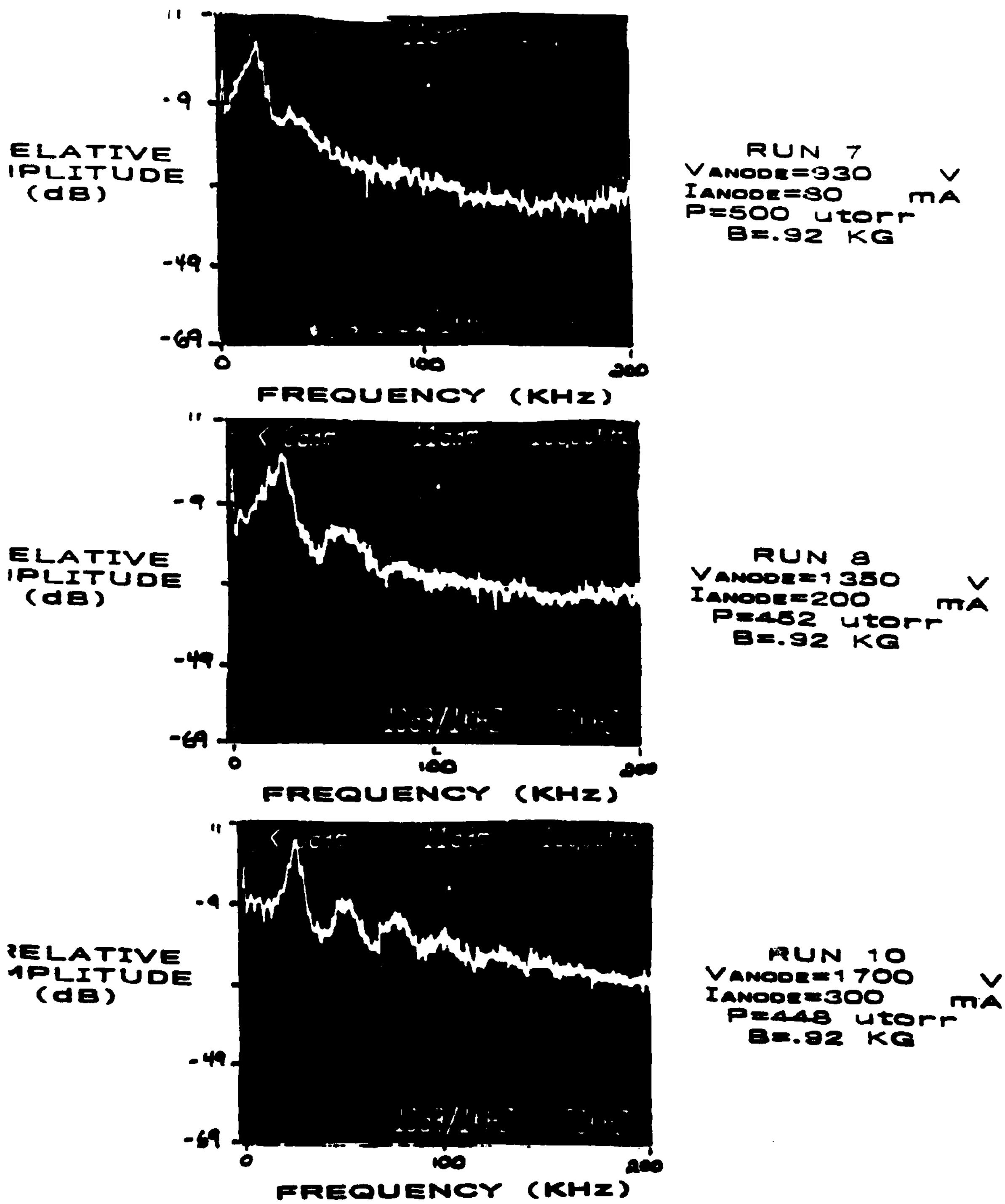
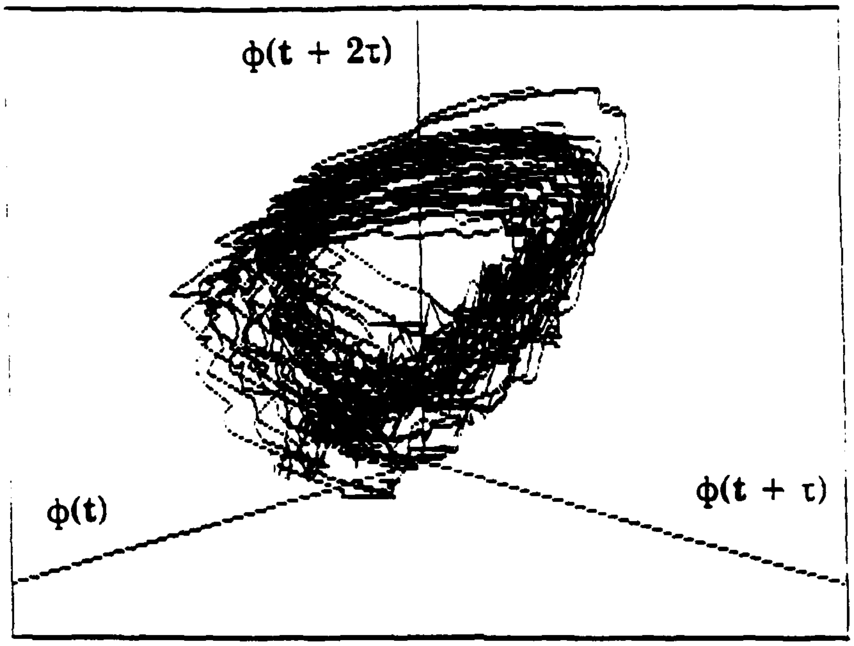
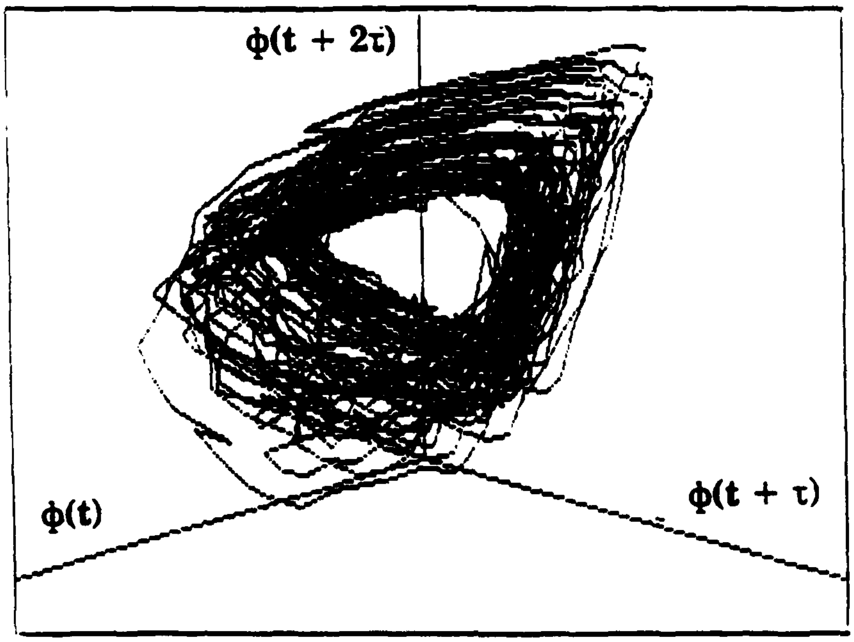


Figure 33

RECONSTRUCTED PHASE PORTRAITS

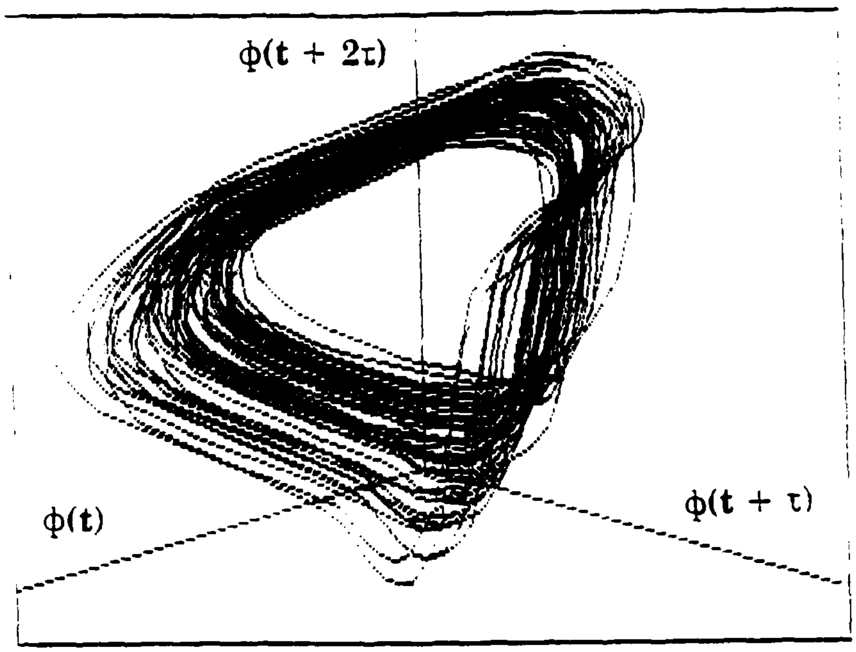


RUN 7



RUN 8

Figure 34



RUN 1

Figure 35

random case of turbulence is shown in Figure 31. Above is the auto power spectrum from 0 to 200 kilohertz, showing a relatively flat, turbulent spectrum with no dominant peaks. The reconstructed phase spectrum shown at the bottom indicates no limit cycle or attractor to the phase trajectory of the fluctuations in this plasma, Figure 32 shows the correlation dimension for this highly turbulent case. A more coherent case is shown in Figure 33, accompanied by the respective reconstructed phase portraits on Figures 34 and 35. Here, a better defined limit cycle, particularly in Figure 35, is apparent. Analysis of these data still continues as of this writing.

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laboratory devoted to exploratory research, a few other topics came up which were done with time and resources made possible by ONR support, even though they represented topics which were not originally proposed for Navy support.

Some of these topics include the abstract on radial equilibrium and force balance in electric field dominated plasma, reported to the APS Plasma Physics Division Meeting in 1981, an abstract of which is on page G-6 of Appendix G. Another such paper was a collaborative paper with Prof. Igor Alexeff on an improved MHD model for the earth's magnetic field, which was presented at the IEEE meeting in 1986, an abstract of which is included on page G-19. Another collaborative paper with Prof. Alexeff was on the two interpenetrating beam instability, also presented at the APS Plasma Division meeting in 1984, an abstract of which is on page G-30.

In the early Spring of 1987, I became interested in the industrial applications of plasma, and saw a way to apply some of the Navy supported research results to industrial plasmas. Accordingly, I prepared a paper on the theory of plasma ion implantation for hardening metals, which I presented at the IEEE conference in Washington, DC, in 1987. An abstract of this paper is included on page G-24 of Appendix G. This paper elicited the largest single number of reprint requests of any of the ONR supported papers which are included in Appendix G. Finally, one of our diagnostic papers, by Saeid Shariati, his Master's thesis on Computer-Aided Reduction of Plasma Data, and one of our diagnostic development papers, was presented at the 1984 IEEE Plasma conference, an abstract of which is included on page G-29 of Appendix G.

Appendix F contains a list of the 31 papers at IEEE, APS, and other plasma related meetings which were supported by the ONR contracts covered by this final report. Appendix D contains a list of the eight archival journal articles which have resulted thus far from the work supported by this contract. I anticipate that at least one more APS paper, two graduate theses, and at least three archival journal articles will be published in addition to those cited above, as a result of the work supported by this 9.25 year program.

POTENTIAL UTILITY OF RESEARCH TO THE NAVY

The basic research on steady state electric field dominated plasmas performed under this contract has potential relevance to several areas of concern to the U.S. Navy. These include the production of broad-band RF emissions suitable for jamming military communications; the enhancement of plasma turbulence, accompanied by plasma heating; the heating of plasma by turbulent energy cascading; the simulation in a steady state, laboratory plasma of RF emission and turbulence-related phenomena which may occur on a microsecond time scale in intense particle beam sources and intense rf sources of weapons interest; the observation of anomalous plasma resistivity, which should allow much higher power densities to be developed than would be possible in plasmas the resistivity of which is dominated by binary particle collisions (Spitzer or Lorentzian resistivity); and modification of plasma transport coefficients by turbulent mode enhancement and damping. More information about these potential areas of application is given below.

Generation of Microwave Power at the Geometric Mean Emission Frequency

The initial focus of our research efforts was phenomena related to the geometric mean emission frequency, a discovery of Roth and Alexeff (see Appendix E, pages E-1 to E-11). This frequency can be written in terms of the plasma electron number density and the atomic mass number A of the ion species as follows,

$$\nu_{gm} = 0.537\sqrt{\nu_{pe}\nu_{pi}} = \frac{737\sqrt{n_e(\mathrm{cm}^{-3})}}{A^{1/4}}\ \mathrm{Hz} \tag{9}$$

RF emission at this frequency has been observed in the classical Penning discharge operated in conjunction with the AFOSR contract at the UTK Plasma Science Laboratory, and has also been apparent in the RF emissions from the modified Penning discharge configuration in the AFOSR experiment. It is possible that the geometric mean emission can be excited in the magnetosphere or in the ionosphere, due to an influx of mirroring or counterstreaming electrons. The emission frequency associated with maximum ionospheric densities and atomic oxygen ions falls within a range of 230 kHz to 1.6 MHz. The lower frequency limit could be much less than 230 kHz if the emission were excited at a plasma density less than the ionospheric maximum.

Efficient Generation of Microwave Power

In Penning discharges, the emitting electrons and ions are trapped by a combination of electrostatic and magnetic trapping. The average particle lifetime is much longer than a single transit time, in contrast to travelling wave tubes where the emitting electrons are not trapped, and pass once through the interaction region in a single transit time. The trapping of electrons and ions in the emitting volume might lead to much higher efficiencies for RF emission than are possible in once-through devices like traveling wave tubes.

High efficiencies, which one might expect for the above reasons, have not been observed in our research program. The ratios of microwave power output to dc input power to the discharge are typically from 10^{-4} to 1% at dc input

power levels on the order of several hundred watts. It may be that the interpenetrating beam mechanism responsible for much of the RF radiation from these plasmas may be a minor, parasitic phenomenon, with the power balance of the discharge dominated under all conditions of operation by volume ionization, line emission, and the production of energetic ions at energies comparable to the anode potential, which are lost to the cathode surface. It also may be the case that the power consumption mechanisms just mentioned may represent fixed losses, which will become less significant as the operating power levels or number density of the discharge are increased. Although the data obtained under this contract give us little reason for encouragement, we have not given up on the possibility of efficient generation of microwave power using the classical Penning discharge, using pulsed plasmas or much higher input powers.

Broadband Microwave Power Generation

Experimental data show that RF emissions occur over a very broad frequency band, from below 0.6 MHz to frequencies as high as 2 GHz. Under the appropriate conditions, the emissions are capable of jamming AM/FM reception in Ferris Hall, the building in which the UTK Plasma Science Laboratory is located. When the plasma operating conditions are just right, the RF emission is a virtually flat white noise spectrum over frequencies up to at least 1 GHz. The physical processes responsible for such a high degree of non-linear mode coupling and for such broad-band RF emission are not yet understood, but are clearly related to the geometric mean emission frequency and accompanying non-linear mode coupling, which give rise to RF emission

at the harmonics of this frequency. This broad-band emission has the potential for development into a useful jamming tool, especially if the emitter were operated on a high power or pulsed basis. The efficiency with which this broadband emission can be generated has been measured at levels from 0.01 to 1.0 percent, under grossly non-optimized operating conditions.

The available experimental data suggest that efficient production of broadband radiation probably is not possible under the conditions with which we have operated our classical Penning discharge. The paired comparison between the classical and modified Penning discharges indicates strongly that the axial magnetic field gradients of the modified Penning discharge increase the efficiency of broadband RF power generation by at least a factor of 10. We find that future work on developing efficient, broadband RF emission from Penning discharges should use the modified Penning discharge configuration, in which the Penning discharge is operated in a magnetic mirror geometry with axial magnetic field gradients. In addition, pulsed operation at high power levels and higher electron number densities also should improve the efficiency of this broadband RF emission.

Processes in High-Power, Pulsed Plasmas

The classical and modified Penning discharges may simulate physical processes that occur in intense particle beam sources and high power microwave sources, but do so in the steady state, and in plasmas of sufficiently low density that conventional diagnostic instruments can be used to measure the characteristics of the plasma and of the resulting RF radiation.

The electric and magnetic geometry of the classical Penning discharge is similar to that of particle beam sources and/or high power microwave sources. In our Penning discharges, relativistic effects are not important, as they would be for intense relativistic electron beam devices. Penning discharges may, however, provide useful information about physical processes in non-relativistic proton beam sources and/or high power microwave sources, in which RF emission at the electron cyclotron frequency is not too important.

Some of our results which may be of interest to those engaged in research on relativistic or high power pulsed microwave and particle sources are the importance of the two interpenetrating beam plasma oscillation; the importance of E/B drift waves in the plasma dynamics; the observation in this plasma of the continuity equation oscillation; observation of the diocotron instability; the production of kilovolt ions with a broad energy distribution, sometimes Maxwellian; and enhancement and damping of the turbulent spectrum by excitation from an "effector" probe. These findings may be of interest for directed energy weapons, or for other technologies that generate ion or electron beams.

High Power Density Plasma Generation

The penetration of electric field dominated plasmas by strong radial and axial electric fields is characteristic of Penning discharges. These electric fields allow the radiating ion and electron populations to be coupled directly to an external dc power supply, thus imparting energy to the radiating species in the same volume in which the RF emission originates. Our research program has demonstrated the existence of axial electric fields of several hundred volts

per centimeter, and turbulence-induced anomalous resistivities of many orders of magnitude above that of binary collisional processes. This research could lead not only to mechanisms for creating plasmas at a very high steady state power density, but also to RF emitters more efficient than single-pass-through devices like the traveling wave tube.

Control of Transport Coefficients by Enhancement or Damping of Turbulent Modes

Perhaps one of the most interesting and exciting possibilities uncovered by our research program is the possibility of controlling the turbulent contributions to plasma or ordinary fluid transport coefficients by adjusting operating conditions to either enhance or damp the nonlinear mode coupling and hence the magnitude of the turbulent spectrum. The level of turbulence in a plasma, or for that matter in an ordinary fluid, is certainly an important influence on such transport coefficients as viscosity, heat and mass transport, and confinement of magneticallycontained plasmas. Our research program has demonstrated, by use of an effector probe, that it is possible to either enhance or to damp the turbulent spectrum, relative to the levels observed in the unexcited, or self excited, turbulent state of the plasma. This has been possible not only because we have adopted a philosophy of active modification of the turbulent spectrum through an effector probe, but also because we have unusually fine experimental equipment, purchased with ONR and AFOSR-URIP funds, which allows us, for example, to observe plasma turbulence over a dynamic range of 80 dB. Our instrumentation also will allow us to measure two signals from the plasma with cross talk between channels of instrumental origin at least 40 db below the signal level. This hardware with low signal

crosstalk makes it possible to assure that any mode coupling that we observe is due to the plasma at least down to this level, and not due to nolinear mode coupling which occurs in our experimental instrumentation.

If we were able to identify the specific factors which enhance or reduce the nonlinear mode coupling in the turbulent spectrum, it would then be possible to control the turbulent contribution to viscosity, cross field radial transport, and radial energy transport in plasma, as well as ordinary fluids. The application to ordinary fluids would be of great interest to the Navy, since turbulent contributions to the viscosity of submarines or aircraft might be greatly reduced if steps analogous to those we have taken in our plasma were taken in those applications.

Application of Nonlinear Dynamics to Plasmas

Turbulent plasmas are present in many applications of interest to the US Navy. Turbulent plasmas occur in the magnetosphere and ionosphere, under conditions which may affect very low frequency submarine communications or Navy radar systems. Not nearly enough is known about the behavior and control of turbulent plasmas. Indeed, even describing turbulent plasmas is difficult, and no well-established set of parameters is available to describe them. The branch of nonlinear dynamics which has come to be known as chaos theory appears to be a promising approach to describing and perhaps understanding the behavior of turbulent plasmas. We have already made some small but significant steps toward describing the characteristics of turbulent plasmas, using chaos theory, in the UTK Plasma Science Laboratory. We have made use of a commercially available computer

program which is capable of calculating the chaos related parameters of the turbulent plasmas which we have observed. Further work along these lines may make it possible to know with a much greater degree of confidence whether the turbulent plasmas used in our laboratory are indeed simulating the turbulent plasmas observed in the ionosphere and magnetosphere which are of Navy interest. In addition to confirming that laboratory and geophysical plasmas are chaotic in the same general sense, and with the same overall chaos-related parameters, applications of these methods from nonlinear dynamics may also allow new insight into the physical processes responsible for plasma turbulence, mode coupling in the frequency spectrum of plasma fluctuations, turbulent heating and energy cascading in the turbulent spectrum, and characterization of the transport coefficients which depend upon scattering of electrons or ions off turbulent fluctuations in the plasma.

RESULTS OF OTHER CONTRACT ACTIVITIES

In addition to the program of experimental research, the results of which are described above, this contract served as a vehicle to accomplish several additional objectives which were important to us here at the University of Tennessee, Knoxville, and which would not have been possible without the support of the Office of Naval Research.

Development of the UTK Plasma Science Laboratory

Although development of the UTK Plasma Science Laboratory was not a goal of this research contract, ONR support has played important role in elevating the research effort in experimental plasma physics at the University of Tennessee from a low level to a "critical mass" of student and faculty research effort in the areas of electric field dominated plasmas, plasma turbulence, and the interaction of RF radiation with high temperature plasmas. Part of the physical impact of Navy support may be seen in Figures 1, 2, 3, 5, and 10, which show the UTK Plasma Science Laboratory before and after building up the modified Penning discharge, on which the research in this report was conducted. In addition to supporting the manpower required to set up and operate this steady-state research facility, the Office of Naval Research has, through the DoD-University Research Instrumentation Program, benefited from an additional $233,000 for state-of-the-art equipment which was provided by the AFOSR in 1985. This equipment has had a major impact on the ONR and other contract research in the UTK Plasma Science Laboratory. The availability of training on this state-of-the-art equipment has not only attracted well qualified research assistants, but also regular graduate and upper division undergraduate students who have worked for us free, for the experience of working with this state-of-the-art equipment. Support by the ONR was instrumental in making the UTK Plasma Science Laboratory, over the past nine years, into an important center in the southeastern United States for the experimental investigation of

plasmas, and the training of students in plasma science and related disciplines.

Early in this 9-year period, the highest priority instrumentation needs for the ONR contract were met by a supplemental $30,000 extension-of-effort grant which we received at the end of the summer, 1983. These funds allowed us to purchase a state-of-the-art LeCroy 3500 minicomputer system with the transient recorder software package. This made it possible for us to use it as a smart X-Y plotter and a smart oscilloscope. neither LeCroy nor any other manufacturer had (or has) plasma-related software for the reduction of retarding potential energy spectra, Langmuir probe traces, etc. and so we were forced to develop our own software. This LeCroy system played a key role in our data-taking and graduate education programs from late 1983 until late 1988, when the LeCroy mainframe (but not the transient recorders) were retired in favor of a new, more powerful IBM AT system.

Support of Graduate Study and Research at UTK

In 1980, there was no externally supported graduate study and research in experimental plasma physics on the UTK campus. With ONR support, the UTK Plasma Science Laboratory now offers students at both the undergraduate and graduate level hands-on training in experimental plasma physics research with state-of-the-art equipment, using diagnostic methods which are at the forefront of university and national lab plasma physics research. The ONR contract provided at least 16 person-years of training at the graduate level, and an addition 4 person-years of training to

undergraduates who were hired with "surplus" funds during the first six years of the contract.

The contributions of this contract to student support and training at UTK extend beyond the salary of 2 research assistants during this research program. During this period, this contract has, at no additional cost to the Navy, supported research on six senior projects; work by five senior students on a three credit hour special projects laboratory course, each for at least one quarter; and a noncredit graduate laboratory course for a physics graduate student. In addition, contact with the experimental apparatus of this contract was incorporated into ECE 369, an undergraduate laboratory course involving several plasma physics experiments. Experimental data from the Navy experiment have been incorporated as homework and quiz problems in ECE 361, our undergraduate introductory course in plasma engineering, and as examples in ECE-NE 561-562, a graduate level course in plasma diagnostics.

Surplus DoD Equipment for Plasma Research

An activity which has greatly increased our inventory of RF and electronic test equipment has been the procurement of free, surplus equipment under the DoD Surplus Propery Utilization Program. This program permits DoD contractors to obtain surplus equipment from DoD installations free of charge, and, since October, 1982, free of shipping charges. After 1987, the Surplus Property Utilization program was further simplified to allow principal investigators of DoD contracts to take the surplus property

back to their laboratories with them, directly from the warehouse, without having to wait for clearance of the property transfer documents.

We have used the ONR contracts covered by this final report as legal vehicles for title to the surplus equipment. We have built up a large inventory, comprising 86 pages of computer printout, and several thousand items with a book (original cost) value of over 1.5 million dollars. All this equipment had been declared surplus at the federal installations where we obtained it. This program has allowed us to build up one of the best academic experimental research laboratories in the country in the area of RF interactions with plasmas, at no cost to the contract, or to the University of Tennessee.

Our first experience with this program was in December, 1982, when the Principal Investigator visited the Warner-Robins Air Force Base just south of Macon, GA, and obtained 24 items of surplus equipment for the UTK Plasma Science Laboratory. Since that time we have made at least one, and usually two, screening trips each year to military or other government installations within a four hour driving radius of Knoxville. These equipment scrounging trips, over a six year period, have allowed us to build up systematically an inventory of microwave hardware for the major frequency bands of interest for Air Force and naval radar systems. We have also obtained used, but serviceable, power supplies, electronic test equipment, signal generators, and a wide variety of other expensive equipment that has greatly facilitated our research program for ONR, and has made possible measurements of a kind that would not have been financially possible without this program.

As an aside, it is very strange that this program is not much more utilized by principal investigators of DoD contracts. The property disposal officers at installations where we got our equipment have told me that microwave and electronic test equipment of the kind we obtained is something for which they had little call, and usually could not get rid of except at scrap prices. Nearly all the equipment which we obtained is at least ten years old, and does not meet state-of-the-art requirements, but nearly all of it is by major manufacturers of good reputation, is in working order, and is in calibration. Some systematic means should probably be found to inform DoD principal investigators of the opportunities provided by this program, perhaps by sending them an informational brochure when they obtain a DoD or ONR contract.

At the present writing, we are taking steps to transfer this surplus property from the ONR to the University of Tennessee. While legal authority exists for transferring equipment purchased under these two contracts to the University of Tennessee, it is a strange circumstance that no legal authority exists for DoD agencies to transfer surplus property directly to contractors like UTK, which have used such surplus equipment. To deal with the surplus equipment in the UTK Plasma Science Laboratory, Mr Eric Anderson of Senator Gore's office has set up an ad hoc procedure by which we are temporarily transferring title to this equipment to a NSF contract here at the University of Tennessee. Before that NSF grant expires, title will be transferred by the NSF to the University of Tennessee.

Obviously, this indirect procedure is cumbersome, and it does not make good sense for it to be much more difficult to transfer to principal investigators

used equipment obtained for contract research which was declared surplus at its point of origin, than it is to transfer new equipment which was bought as part of the contract. I would strongly recommend that the ONR/DoD contact appropriate individuals in Congress, with the objective of putting in place legislation which will enable surplus equipment to be transferred to DoD contractors, on the same basis on which newly purchased equipment is now routinely transferred. Finally, I would like to express my appreciation for the very competent assistance of Mr. Thomas A. Bryant of the ONR Atlanta Office, without whose help theproperty transfer process could not have been accomplished.

INTERACTIONS WITH OTHER RESEARCH PROGRAMS

Publications

The progress made and research results obtained under this contract have been systematically documented in Iterim Scientific Reports and Status Reports; in the 31 conference presentations described in the next section of this report; in 8 archival papers presented at international scientific meetings and published in recognized scientific journals; and as final reports of completed work in the form of masters or Ph.D. theses which acknowledge ONR support, available through University Microfilms.

Copies of the Interim Scientific and Status Reports on this research program are already in the hands of the ONR; abstracts of the 31 oral and poster conference presentations are included in Appendix G; reprints of the 8 archival scientific papers are included in Appendix E of this report. Abstracts, tables of contents, and the title page from the Interim Scientific and Stat

Reports are included in Appendix I of this report, and the abstracts, tables of contents,and title pages of the theses already published and supported by this contract are listed in Appendix H.

Conference Presentations

In addition to the archival and detailed full-length reports of completed work described in the previous section, and documented in Appendices D, E, H, and I, of this report, there were numerous conference presentations listed in Appendix F in which progress on this research program was reported to our professional peers. We have made it a practice to regularly present progress reports on the activities of this contract at the IEEE International Conference on Plasma Science, held on May of each year, and also at the annual meeting of the American Physical Society's Plasma Physics Division, usually held early November of each year. Most of these conference presentations were in poster format, and were progress reports covering he previous six months of activity under this contract. The poster and/or transparency materials for most of these presentations were contained in the Interim Scientific or Status Reports listed in Appendix I.

Presentation of the work done under this contract at these conferences allowed us to interact with other investigators from such DoD laboratories as the Naval Research Laboratory, Edwards Air Force Base, the Kirtland Air Force Base, the Wright-Patterson Air Force Base, the Harry Diamond Laboratories, as well as many other DoE and DoD Principal Investigators of university contracts,at such universities as the University of Iowa, the Universityof Wisconsin, the University of Texas at Austin, the Polytechnic

University of New York, the University of Miami at Coral Gables, Texas Tech University, and others.

Collaboration with the University of Texas, Austin

The software required to obtain auto-and cross-power spectra and other statistical properties of plasma fluctuations was originally developed by Professor Edward J. Powers of the University of Texas at Austin and his students. This computer program has been made available to us by Prof. Powers, and has been modified and entered into our mainframe computers at UTK. Professor Powers' program is based on a fast Fourier transform of the incoming time series supplied by the analog-to-digital data handling system, and produces auto power spectra,cross power spectra, phase spectra, coherence spectra, transport spectra, and a plot of the time series itself for the 3 simultaneous input channels of information. This software also has been used to obtain the fluctuation data which we presented at meetings. Mr. Paul Spence from the UTK Plasma Science Laboratory traveled to the University of Texas at Austin in March, 1985, and was given additional software programs for bispectral analysis of digital time series, and other programs which were extremely useful in studying fluctuations and turbulence in plasmas.

DoD Contracts at the UTK Plasma Science Laboratory

During the 9.25-year period of this report, the UTK Plasma Science Laboratory was supported by five DoD contracts. The first research contract to be awarded was ONR-N00014-80-C-0063 (Roth), Dr. Charles W. Roberson,

Technical Monitor. This contract was granted on January 1, 1980, and extended through September 30, 1987. This contract is concerned with exploratory experimental investigations of the physical processes in electric field dominated plasmas generated in the steady state by a modified Penning discharge located in an axisymmetric magnetic mirror geometry. These investigations focused on RF emissions from the plasma, non-linear mode coupling of plasma fluctuations, axial electric field profiles, and other phenomena which may be related to, or have analogs in, the magnetosphere. This research program was extended to March 31, 1989 under ONR contract N00014-88-K-0174.

The second contract to be awarded to the UTK Plasma Science Laboratory was AFOSR-81-0093 (Roth), which started on March 15, 1981, and terminated on March 14, 1986. This contract was concerned with the investigation of physical processes in an electric field dominated plasma produced by steady-state operation of a classical Penning discharge with an approximately uniform axial magnetic field profile. The phenomena of particular interest in this investigaton were anomalous plasma resistivity, axial electric field profiles, plasma turbulence, turbulent heating of ions, non-linear phenomena relating to energy dissipation in the plasma, and plasma heating by collisional magnetic pumping.

Professor Igor Alexeff of the UTK Department of Electrical Engineering has held AFOSR contract 82-0045, which terminated on March 14, 1986. This contract covered the development of a submillimeter microwave emitter based on the Orbitron configuration. Prof. Alexeff holds a US patent on this device, and under AFOSR sponsorship, has analyzed its operation and instabilities

theoretically, while pursuing an experimental program which has achieved steady state operation, and generated wavelengths down to 0.3 millimeters. The Orbitron configuration has attracted interest at the Naval Research Laboratory, at the Hughes Research Laboratories, and other places where advanced research on microwave emitters is conducted.

The above two AFOSR contracts, AFOSR-81-003 (Roth), and AFOSR 82-0045 (Alexeff) were combined in a three-year follow-on contract, AFOSR-86-0100 (Roth) which supported, for a period of three years ending on March 14, 1989, the combined research efforts of J. R. Roth and Igor Alexeff, with Dr. Robert J. Barker of AFOSR as program manager. Under Prof. Roth, the main thrust of this contract research is the theoretical and experimental study of collisional magnetic pumping as a plasma heating method; under Prof. Alexeff the thrust of his research program is further development of the Orbitron microwave emitter.

In addition to the above four contracts, Prof. J. Reece Roth was Principal Investigator of a 6-month, Short-Term Innovative Research Program Grant from the Army Research Office (ARO) on "Corrosion Inhibition by Plasma Ion Implantation." This contract extended from July 1, 1988 to December 31, 1988 and was under the program management of Dr. Robert Reeber of the Materials Science Division of ARO. This work is being continued with UTK funds until June 1, 1989, after which time we hope to have additional funding in place from either the ARO or NSF.

All three of the non-ONR contracts mentioned above have contributed to a critical mass of expertise and effort at the UTK Plasma Science Laboratory. Each of the five contracts have contributed diagnostic methods and equipment

to the common pool available to the graduate students and research programs supported by the ONR.

Comparison of Classical and Modified Penning Discharges

The research contracts with the AFOSR and Office of Naval Research have been operated in parallel, and have shared much of the same computer software, diagnostic equipment, electronic test equipment, power supplies, microwave equipment, and other facilities of the UTK Plasma Science Laboratory. Nonetheless, each contract has had a different set of goals and objectives, with the exploratory research for ONR being conducted for most of this 9.25-year period on a modified Penning discharge, a Penning discharge operated in a magnetic mirror field with a 5:1 variation of magnetic field along the axis; and the AFOSR exploratory research conducted in a classical Penning discharge, with a uniform magnetic field along its axis.

The availability of two different kinds of Penning discharge operating in the steady-state, and in the same laboratory, made possible a paired comparison of the properties of these two forms of Penning discharge. This comparison was explored in the archival papers included in Appendix E, which were presented at the 1982 and 1984 International Conferences on Plasma Physics.

These paired comparison experiments on the two types of discharge established that the axial magnetic field gradients in the ONR experiment greatly enhanced the axial electric fields observed, and it also established that the level of RF emission was from a factor of 10 to a factor of 100 greater from the ONR modified Penning discharge than it is from the classical Penning

discharge supported by the Air Force contract. Both Penning discharge plasmas had approximately the same type of "catastrophic" current-voltage curve, with hysteresis and discontinuous jumps on the current-voltage diagram. Both functioned in two distinct modes of operation, and they tended to operate over the same general range of electron and neutral number densities. Other points of similarity and difference are discussed in the papers included in Appendices D and E.

The AFOSR Undergraduate Research Fellowship Program

The UTK-AFOSR Summer Undergraduate Research Fellowship Program has been underway at the UTK Plasma Science Laboratory since the summer of 1985. It has benefited the ONR research program as well as that of the Air Force. The objectives of the program are to train students in state-of-the-art methods and the use of state-of-the-art equipment; to make promising undergraduates familiar with DoD research and development; to introduce promising undergraduates to graduate study and research; to keep the manpower pipeline filled which supplies our country's future manpower pool for advanced research and development; to facilitate and contribute to ongoing university research programs funded by the Air Force at the UTK Plasma Science Laboratory; and to recruit promising undergraduate students into graduate study and research at UTK and at the UTK Plasma Science Laboratory. The latter objective is ours, and is not that of the AFOSR.

The requirements of this program are that participants be U.S. citizens, that they be an undergraduate student of engineering or physics, that they must have completed a minimum of 8 quarters or five semesters toward an

appropriate bachelors degree, that they be interested in hands-on experimental work, and that they have a grade point average of at least 3.20 on a scale of 4.0. In addition, we give preference to students who are interested in pursuing careers in plasma science or plasma physics.

The conditions of tenure for this program are that participants come to the UTK campus for a ten week program from early June to early August in the summer. They are expected to do full time work, 40 hours a week, for a gross pay of $3,000 for the ten weeks. We make available to them a UTK dormitory room for about $45.00 per week. We ask them to spend 20% of their effort on housekeeping activities in the UTK Plasma Science Laboratory, and devote 80% of their efforts over the summer on a single project which is designed either to take publishable data (some of our past summer students have appeared as co-authors on papers published out of the UTK Plasma Science Laboratory) or build up diagnostic or other equipment needed in our contract research. The students are expected at the end of the summer to write up a report on their projects, and present this orally to their peers during the last two days of the summer program. They are also expected to attend scheduled seminars every day for the first three weeks of the program, and at least once or twice a week after that. Most of these lectures are intended to give them background information which will be useful to them in making career choices, selecting graduate schools, and understanding the physics behind projects in the UTK Plasma Science Laboratory. In addition, we offer equipment tutorials on various diagnostic equipment in the Plasma Lab and on some of our more sophisticated instruments.

This program offers a number of opportunities for students. They can obtain experience with state-of-the-art equipment which is not normally available to them in undergraduate physics or electrical engineering programs; they can learn useful skills in computer programming, vacuum technique, plasma diagnostics, microwave circuits, laboratory safety, etc. Their experience in the Plasma Lab gives them an opportunity to broaden their experience through orientation lectures, equipment tutorials, and weekly seminars involving faculty from the UTK Electrical & Computer Engineering Department who describe graduate level research in their respective areas. Our summer students also have an opportunity to observe graduate study and research at first hand, and to try their hand at research in plasma science or plasma physics. If they wish, they can earn academic credit for a senior project lab by registering for such a course at the UTK campus. In addition, several of our students in the past have used their summer project as the basis for a paper in a student paper competition. The student paper contest at the IEEE Southeastcon meeting has had a plasma-related entry from one of our summer students place first, second, or third each year for the past three years.

This program started in 1985 with a relatively modest effort because of the very short time we had to get it organized. Funds only became available in early May for a program that started in mid June. That first year, we had six students and there was no off-campus recruiting because of insufficient time. The average GPA of those students was 3.4, and all but one went on to do graduate study. We had 14 weeks of half time activity and we did not have any orientation or equipment tutorial lectures during that first year. Of the

six students, five were male and one female, and we only required them to work half time, or 20 hours a week.

In the summer of 1986, during the second year of the program, we had 26 applicants for 10 posts. Five women and twenty one men applied, and only four were from off campus. Of the final ten students, nine were male and one female and only one was from off campus. All the off campus recruiting was done by direct mail, and there was no recruiting through electrical engineering or physics department heads. We did our on campus recruiting by direct mail and bulletin boards. The average GPA that second year was 3.7, and at least eight of the ten went on to do graduate study. That summer program also lasted 14 weeks, at a half time level of effort, and a $500 per month salary. We had an orientation and final lecture and equipment tutorials organized that year.

During the third year of the program in the summer of 1987, we had 24 applicants for ten posts. Two of the applicants were female the rest male, and 21 of the 24 were from off campus. This improvement in off campus recruiting occured because we sent announcements, a brochure, and an application blank to 600 four-year EE department heads and 200 physics department heads in the eastern United States. Of the final ten students, one was female, and seven were from off campus. The on campus recruiting was done by bulletin boards only. The average GPA this third year was 3.54, and this time we required a ten week summer program of full time, 40 hour a week work, at a salary of $2,500 for the ten week period.

In the summer of 1988, the fourth year of the program, we had 15 applicants with grade point averages between 3.5 and 4.0 on a scale of 4.0. Of

these 15 applicants, one was female and 14 were male and twelve of the 15 applicants were from off campus. Of the students selected for the program there was one women and seven men, and five of the eight students were from off campus. The affiliations of the off campus students in 1988 included Auburn University, Bethany College, Brown University, Indiana University the College of Charleston in Charleston, SC, and UTK.

Other Presentations, Visits, and Reviews

During this contract, the Principal Investigator has interacted with a number of outside individuals and organizations. He has given invited talks at the IEEE Conference on Plasma Science in St. Louis; at Cornell University, where he also interacted with John Nation and the ion beam plasma group; at the University of Illinois, in October, 1985; and at the University of Texas at Austin, in November, 1985. Professor Roth also attended the International Conference on Plasma Physics in Goteborg, Sweden in June, 1982, and the same conference in Lausanne, Switzerland in late June, 1984. While in Europe, Prof. Roth visited plasma laboratories in Grenoble, France, Garching, West Germany, and Culham, England before or after these conferences. Other invited lectures and seminar presentations of the Principal Investigator are listed in Table II, below. Service by the P. I. on national boards and committees is listed in Table III.

During this research program, the UTK Plasma Science Laboratory was visited by Professor Edward J. Powers of the Electrical Engineering Department of the University of Texas, Austin and Professor George Miley, of the Nuclear Engineering Department at the University of Illinois. Dr. Robert

Barker visited on January 20 and 21st, 1985 to give a seminar to faculty and graduate students on his plasma physics work. He also visited on September 18th and 19th, 1985, to give a presentation on Air Force Research programs for our seminar participants, and to evaluate the summer pilot program for undergraduate research assistants. He again visited on March 12 through 14 1986, for a contract signing ceremony. Some photographs taken during this contract signing ceremony are included as Figures 36 to 39. Finally, Dr. Osmau Ishihara gave a seminar on his work on an MHD-based tokamak current drive mechanism and other work in the Electrical Engineering Department of the Texas Tech University in Lubbock, Texas.

Figure 36

Figure 37

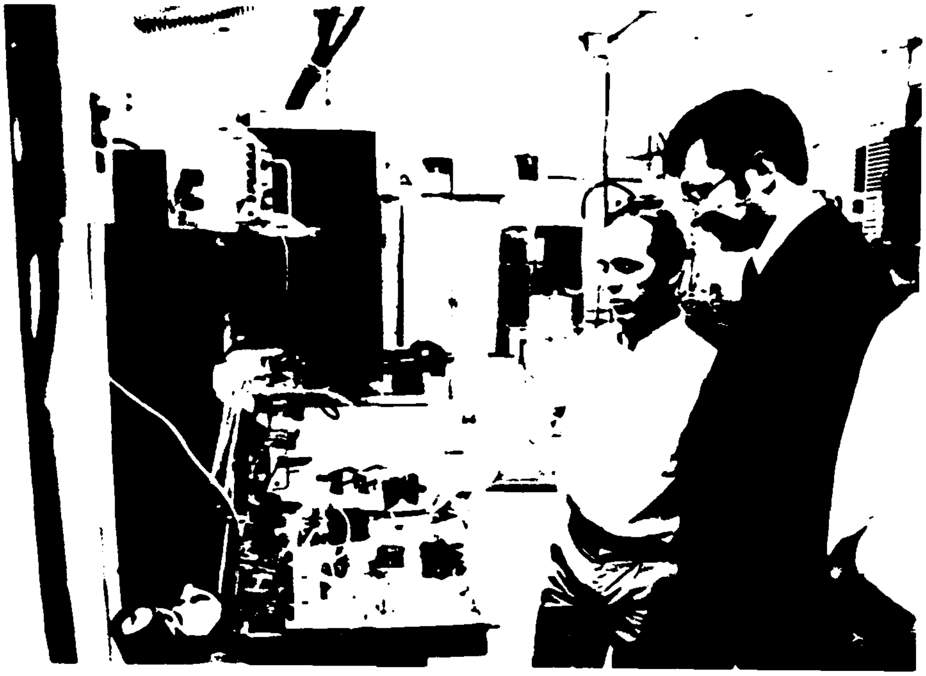

Figure 38

Figure 39

Table II

INTERACTIONS AT INVITED SEMINARS AND LECTURES

a) Interactions off the UTK campus

1. Hayman, P.W.; and Roth, J.R.: INVITED PAPER, "A Comparison of Mainline and Alternate Approaches to Fusion Energy", Paper 1D4, Conference Record IEEE84CH1958-8, 1984 IEEE International Conference on Plasma Science, May 14-16, St. Louis, Missouri, p. (1984).

2. "Comparison of Mainline and Alternate Concept Magnetic Fusion Reactions", Seminar to the University of Illinois Fusion Studies Laboratory, Oct. 15, 1985.

3. "A Generalized Analysis of Power Balance for Fusion Reactors", Nuclear Engineering Seminar, University of Illinois, Oct. 15, 1985.

4. "Plasma Turbulence Experiments at the UTK Plasma Science Laboratory", Electrical Engineering Seminar, University of Texas at Austin, Nov. 20, 1985.

5. "A Generalized Analysis of Fusion Powerplants", Fusion Engineering Design Center Seminar, ORNL, Jan. 8, 1986.

6. "Experimental Research on Plasma Instabilities and Turbulence at the University of Tennessee", Laboratory of Plasma Studies Seminar, Cornell University, Ithaca, New York, April 11, 1986.

7. Participant in the Gordon Conference on Plasma Chemistry, Tilton, NH, August 11-15, 1986.

8. "Recent Developments in Aneutronic Fusion for DoD Space Power and Propulsion Systems" Fusion Engineering Design Center Seminar, ORNL, Jan. 8, 1987.

9. "Experimental Research on Plasma Collisions, Heating, and Turbulence at the UTK Plasma Science Laboratory", Plasma Physics Seminar, Naval Research Laboratory, Washington, D.C. February 20, 1987.

b) Within the UTK Campus Community

1. "The Role of Mechanical Engineering in Fusion Engineering", Seminar to the Student Chapter of AIAA-ASME, Feb. 23, 1984.

2. Two lectures quarterly at the EE Department's Plasma Science Seminar Series.

3. "The Biological Effects of Electromagnetic Radiation-Issues and Research Opportunities" Microbiology Departmental Seminar, October 20, 1986.

Table III

INTERACTIONS WITH NATIONAL BOARDS AND COMMITTEES

Service on National Boards and Committees

1) Consultive panel member, Advanced Fuel Fusion Development Section for DoE Office of Fusion Energy's Technical Planning Activity (TPA) Report (Long-Range Planning Document), 1985-86.

2) Member, National Academy of Sciences-National Research Council's Committee on Advanced Fusion Power, sponsored by the Air Force Studies Board, 1986-87.

3) Chairman, Subcommittee on Space-Related Performance parameters and Constraints of NAS-NRC's Committee on Aneutronic Fusion-Phase 1, 1986-87.

4) Workshop participant, NASA-Lewis Research Center's Lunar ^{3}He Workshop, April, 1988, Cleveland, Ohio.

5) Member, AFOSR Advisory Committee to the Air Force Geophysics Research Laboratory, Hanscom AFB, Massachusetts, May, 1988, Workshop on Atmospheric Interactions with Plasmas.

6) Invited speaker, ANS Minicourse on Fusion Applications in Space, Salt Lake City, UT, Oct. 1988.

In addition to the above interactions, we have been keeping in contact with other Principal Investigators and researchers in the general area of plasma heating and turbulence covered by this contract. At the Annual Meeting of the APS Plasma Physics Division and at the IEEE Conference on Plasma Science, we had occasion to interact with individuals doing similar research at the Naval Research Laboratory, at Cornell University, at the Polytechnic University of New York, at the Physics Department at the University of Miami at Coral Gables, at the Edwards Air Force Base, at the Kirtland Air Force Base, at the Harry Diamond Laboratories, at the University of Texas at Austin, at Texas Tech University at Lubbock, at the University of Wisconsin, and many other academic laboratories supported by AFOSR, ONR, and the Department of Energy.

Media Coverage

Unlike much larger metropolitan areas, the city of Knoxville is small enough that activities such as ONR support of research at the UTK Plasma Lab attract media attention. Over the 9.25 year span of ONR support, our activities have resulted in much favorable publicity for the UTK Plasma Science Lab, the University of Tennessee at Knoxville, and the Office of Naval Research. In Appendix K is included media stories which feature the ONR Research Program and the UTK Plasma Science Laboratory. Most of these stories are specifically about the ONR Research program. These 18 news stories have done much to increase the visibility of the Office of Naval Research within the UTK academic community, in the city of Knoxville, and in East Tennessee.

STAFFING

Faculty Investigator

This program of research has utilized the services of Prof. J. Reece Roth as Principal Investigator. His professional background is described briefly below, and his vita are included in Appendix A.

Professor J. Reece Roth

In the past twenty-five years, Dr. Roth has authored or co-authored 107 archival publications, of which 70 were articles in refereed journals or conference proceedings, and the remainder of which were internally reviewed NASA reports. Dr. Roth has published in the Physics of Fluids, the Review of Scientific Instruments, the IEEE Transactions on Plasma Science, Physical Review Letters, Plasma Physics, Nuclear Fusion, the Journal of Applied Physics, the Journal of Fusion Energy, the Journal of Nuclear Instruments and Methods, the Journal of Spacecraft and Rockets, Fusion Technology, the Journal of Mathematical Physics, Nature, and elsewhere. In addition to these publications, Dr. Roth has been author or co-author of 89 oral or poster presentations at professional society meetings, nearly all of which report experimental data on his scientific or engineering work.

While at the NASA Lewis Research Center, Dr. Roth made two pioneering contributions to fusion-related superconducting magnet technology. He was responsible for the basic design and distinctive features of the "Pilot Rig" superconducting magnet facility at NASA Lewis in Cleveland. This facility went into service in December, 1964, and was the first such facility ever to be used for plasma physics or controlled fusion research. Dr.

Roth's second contribution in the magnet area was as the engineer responsible for the basic design and distinctive features of the NASA Lewis superconducting bumpy torus magnet facility. This facility was the first anywhere in the world to generate a toroidal magnetic field.

In studying the plasma which these facilities were designed to confine, Dr. Roth discovered two previously unrecognized modes of plasma instability. The first of these is the "continuity-equation oscillation" (the name is Dr. Roth's own) which was observed in the Pilot Rig in 1967. Dr. Roth was the first to investigate this oscillation experimentally, and the first to describe it theoretically. His work on the continuity-equation oscillation has been recognized in standard monographs and compilations such as A. I. Akhiezer et al. Plasma Electrodynamics, and F. Cap's Handbook on Plasma Instabilities, Vol. 1. Dr. Roth as also the first to report the experimental observation of the "Geometric Mean Plasma Emission" (Dr. Roth also named this instability). His data were explained theoretically by Professor Igor Alexeff, and they jointly reported the discovery of this new instability in August, 1979.

Dr. Roth initiated research on the electric field bumpy torus concept, an approach to creating a plasma of fusion interest in which strong radial electric fields are imposed on a bumpy torus plasma, in such a way that they contribute to the heating, stability, and confinement of the plasma. Dr. Roth has authoritative knowledge of Penning discharges; the use of superconducting magnetic facilities in plasma and fusion applications; the continuity-equation oscillation and moving striations; ion heating and transport in a modified Penning discharge; high temperature plasma physics; fusion energy; and fusion technology.

Dr. Roth was the first to identify the physical mechanism responsible for ion heating in a modified Penning discharge, and the first to describe it. Dr. Roth's academic responsibilities have included teaching a required undergraduate course on plasma engineering from his own notes, a two-semester sequence on fusion energy, from his own textbook, and a two-semester doctoral level course on plasma physics.

Student Training and Development

During this 9.25-year research program, travel funds were set aside for our graduate assistants, where this was necessary to their training and intellectual development. In the past six years, we have made it a custom to take at least our most senior ONR graduate research assistant with us to the IEEE and APS plasma meetings, and did this even on years when these meetings were west of the Mississippi River. On several years, we were able to take both ONR GRA's to these meetings.

We intend to continue our weekly plasma seminars, the program of which, for the past several academic years, is in Appendix C of this report. We also have broadened the horizons of our graduate research assistants by having them travel to other universities as well as to meetings. Our graduate research assistants have also accompanied Prof. Roth on screening trips for surplus equipment at various DoD installations, which are within a half-day's driving radius of Knoxville.

Student Manpower History

The 9-year staffing of this contract is shown on Table IV. The nine years are shown in the first column, with the contract duration and personnel

involved during that year in the second and third columns. The status of the personnel are listed on the fourth column, along with the duration of time during the 12 month contract that they were affiliated with it. The fraction of the time which they were paid to devote to the contract while they were employed under it is indicated in the 6th column. The highest degree obtained by the individual at UTK during or after his association with this contract is in the 7th column, and whether or not that individual did his thesis research in the UTK Plasma Lab is indicated in the 8th column. The penultimate column lists the organization at which the individual is now working, or was last known to be working, and his current status at that organization is indicated in the last column.

One of the principal functions of the UTK Plasma Science Laboratory, as part of an academic institution, is student training and research. In the past, prior to 1980, Ph.D. students trained at the UTK Plasma Science Laboratory have found employment in plasma-related posts all over the United States. Four such students in DoD-related agencies include Dr. Marshall Saylors, who is now working at the National Security Agency; Dr. Melvin Widner, who is working in the field of ion beam fusion at the Sandia National Laboratory; Dr. Kent Estabrook, who is currently doing research on laser fusion at the Lawrence Livermore National Laboratory; and Dr. Larry Barnett, who is doing research on microwave tube development, including gyrotrons and beam-plasma research, at the University of Utah. These students of ours all appear to be doing quite well.

Prior to 1980, there was a very low level of externally supported graduate study and research in experimental plasma physics on the UTK

campus. With Air Force and ONR support, the UTK Plasma Science Laboratory now offers students at both the undergraduate and graduate level hands-on training in experimental plasma physics research with state-of-the-art equipment, using diagnostic methods which are at the forefront of university and national lab plasma physics research. The research effort summarized in this report supported faculty and graduate student assistants at the levels indicated in Table IV.

Table IV

Contract Staffing History

Year	Contract Duration	Personnel	Status	Duration of Service Months	Yearly Fraction of Time	Highest Degree at UTK	Degree Research Done at UTK Plasma Lab	Now Working At	Current Status
1	1/1/80-12/31/80	J. Reece Roth	Prof. P.I.	9	0.25	----	----	---	---
		David Smith	UGRA	6	0.50	B.S.E.E.	No	Tennessee Eastman	Employee
2	1/1/81-9/30/81	J. Reece Roth	Prof., P. I.	12	0.25	---	---	---	---
		David Smith	UGRA	6	0.50	B.S.E.E.	No	Tennessee Eastman	Employee
		Blair Finkelstein	UGRA	6	0.50	B.S.E.E.	No	University of Arizona	Ph.D. Student, Lasers
		Paul Hayman	GRA	9	0.50	M.S.	Yes	Idaho Electric Utility	Engineer, P.E.
		Roger Richardson	Summer GRA	3	0.50	B.S.E.E.	No	Hughes, CA	Got M.S.E.E. at MIT Now Research Engineer
		Hamid Karimy	UGRA	4	0.25	B.S.E.E.	No	---	---
3	10/1/81-9/30/82	J. Reece Roth	Prof. P.I.	12	0.25	---	---	---	---
		Lynn Casson	Summer GRA	3	0.50	M.S.	No	Roane State College	Faculty
		Blair Finkelstein	UGRA	12	0.50	B.S.E.E.	No	University of Arizona	Ph.D. Student, Lasers
		Paul Hayman	GRA	12	0.50	M.S.	Yes	Idaho Electric Utility	Engineer, P. E.
4	10/1/82-9/30/83	J. Reece Roth	Prof., P.I.	12	0.25	---	---	---	---
		Blair Finkelstein	UGRA	5	0.50	B.S.E.E.	No	University of Arizona	Ph.D. Student, Lasers
		Paul Hayman	GRA	5	0.50	M.S.	Yes	Idaho Electric Utility	Engineer, P. E.
		Paul Spence	GRA	9	0.50	Ph.D.	Yes	UTK	Student
5	10/1/83-9/30/84	J. Reece Roth	Prof., P.I.	12	0.25	---	---	---	---
		Paul Spence	GRA	12	0.50	Ph.D.	Yes	UTK	Student
		Saeid Shiriati	GRA	9	0.50	M.S.	Yes	G.E., Cincinatti, OH	Engineer
		Peyman Dehkordi	GRA	12	0.50	M.S.	No	Spinlab, UTK Student	Development Engineer
6	10/1/84-9/30/85	J. Reece Roth	Prof., P.I.	12	0.25	---	---	---	---
		John Crowley	Summer GRA	3	0.50	M.S.	Yes	E.O.L., UTK MBA Student	Engineer
		RezaGhayspoor	GRA	12	0.50	M.S.	Yes	ON RT. 128, Boston	Development Engineer
		Paul Spence	GRA	12	0.50	Ph.D.	Yes	UTK	Student

Table IV
Contract Staffing History (Continued)

Year	Contract Duration	Personnel	Status	Duration of Service Months	Yearly Fraction of Time	Highest Degree at UTK	Degree Research Done at UTK Plasma Lab	Now Working At	Current Status
7	10/1/85-9/30/86	J. Reece Roth	Prof. P.I.	12	0.25	- - - -	- - - -	- - -	- - -
		Paul Spence	GRA	12	0.50	Ph.D.	Yes	UTK	Student
		Jerry Richardson	UGRA	10	0.25	B.S.E.E.	No	TVA	Engineer
		Reza Ghayspoor	GRA	7	0.50	M.S.	Yes	ON RT. 128, Boston	Development Engineer
8	10/1/86-9/30/87	J. Reece Roth	Prof. P.I.	12	0.25	- - - -	- - - -	- - -	- - -
		Paul Spence	GRA	12	0.50	Ph.D.	Yes	UTK	Student
		Min Wu	GRA	12	0.50	M.S.	Yes	UTK	Student
		John Crowley	GRA	4	0.50	M.S.	Yes	UTK	Student
		Ali Keshavarzi	Summer GRA	3	0.50	B.S.E.E.	No	Purdue University	Ph.D. Student
9	10/1/87-9/30/88	J. Reece Roth	Prof. P.I.	12	0.25	- - - -	- - - -	- - - -	- - - -
		Paul Spence	GRA	12	0.50	Ph.D.	Yes	UTK	Student
		Min Wu	GRA	12	0.50	M.S.	Yes	UTK	Student
		Scott Stafford	GRA	1	0.50	M.S.	Yes	UTK	Student
10	10/1/88-3/31/89	J. Reece Roth	Prof. P.I.	6	0.25	- - - -	- - - -	- - - -	- - - -
		Scott Stafford	GRA	3	0.50	M.S.	Yes	UTK	Student

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APPENDIX A

Resume of Principal Investigator

September, 1988

PROFESSIONAL RESUME

J. Reece Roth
Department of Electrical and Computer Engineering
The University of Tennessee
Knoxville, Tennessee 37996-2100
(615) 974-4446
FTS 855-4446

I. PERSONAL

Birthdate: September 19, 1937
Marital Status: Married, two children
Health Status: No physical handicaps

II. EDUCATIONAL

College: Massachusetts Institute of Technology, graduated in June 1959 with a S.B. in Physics.

Graduate: Entered Cornell University in September 1959, graduated in June 1963 with the Ph.D. Major: Engineering Physics. Minor subjects: Magnetohydrodynamics and Astrophysics.

III. PROFESSIONAL EXPERIENCE

1. 1963 to 1978, Member of the Plasma Physics Branch of the Physical Science Division at the NASA Lewis Research Center in Cleveland, Ohio. Was Principal Investigator of the NASA Lewis Bumpy Torus Project.

2. September 1978 to June, 1982. Visiting Professor of Electrical Engineering, University of Tennessee, Knoxville. Principal Investigator of two research contracts in the field of electric field dominated plasma, one with the ONR, the other with AFOSR. In addition to research, taught a junior level course on plasma engineering, a graduate sequence on fusion technology, plasma diagnostics, and physics of fusion, also taught one-week minicourses on fusion energy and fusion diagnostics.

3. June 1982 to August, 1983. Research Professor, Department of Physics.

4. September 1983 to present. Professor of Electrical Engineering and Chairman of the departmental Plasma Engineering Curriculum Committee. Continuation of contract research, and teaching of a graduate course sequence in Plasma Diagnostics, a senior-level course "Introduction to Fusion Energy," and a junior-level course in Plasma Engineering. Published a textbook, "Introduction to Fusion Energy" in December, 1986.

IV. CONTRACTS AND EXTERNAL SUPPORT

Principal Investigator of contracts with ONR, AFOSR, ARO and TVA which, since 1980, will bring in $1,437,870 by the time present contracts run out in early 1989. These contracts will yield a total overhead of $368,385 to the University at that time. They also have provided $278,464 in special equipment grants which have been used to purchase new, state-of-the art diagnostic equipment for the UTK Plasma Science Laboratory. These contracts also made it possible to acquire surplus instruments and equipment from the Department of Defense with a replacment value exceeding one million dollars. These contracts will provide 4.50 man-years of faculty support and 35.7 student-years of support when the last contract runs out.

V. HONORS, AWARDS, AND LISTINGS

Relevant student honors include a four-year Alfred P. Sloan Scholarship at M.I.T., Presidency of the M.I.T. Rocket Research Society, the 1957 American Rocket Society-Chrysler Corporation's Student Award, and a Ford Fellowship at Cornell. Life Member of Sigma Xi, Fellow of IEEE, Senior member of AIAA and co-recipient of one of NASA's "Awareness" awards to the Bumpy Torus Project. Listed in "Who's Who in the Midwest," 1970 to 1978 Editions; "Who's Who in the South and Southwest, "17th Edition, Who's Who in America, 43rd and 44th Editions.

VI. PROFESSIONAL SOCIETY MEMBERSHIPS

1. Fellow of the IEEE
2. Life member of Sigma Xi
3. Life member of the AAAS
4. Senior Member of the AIAA
5. Member of the American Physical Society
6. Member of the American Nuclear Society
7. Member of American Society for Engineering Education
8. Member of the IEEE Nuclear and Plasma Sciences Society
9. Member of the Archaeological Institute of America
10. Member of the University Fusion Association

VII. PROFESSIONAL SOCIETY ACTIVITIES

1. Associate Editor, IEEE Transactions on Plasma Science, 1973-1987.
2. Elected Member-at-Large of Administrative Committee, IEEE Nuclear and Plasma Sciences Society, 1974-77.
3. Secretary, NPSS Administrative Committee, 1975.
4. Organizing Committee, IEEE Plasma Science and Applications Committee, 1971-73.
5. Elected Member, Executive Committee of IEEE Plasma Science and Applications Committee, 1974-77, 1980-82, 1985-87.
6. Member of the Program Committee, IEEE International Conferences on Plasma Science, 1974, 1975.

7. Member, Executive Committee, Northern Ohio Section of the American Nuclear Society, 1975-1978.
8. Member, AIAA Plasmadynamics Technical Committee, 1979 to 1981.
9. Director, and Member of Executive Committee, East Tennessee Section of the IEEE, 1982-83, 1988-90.
10. Vice Chairman, East Tennessee Section of the IEEE, 1983-84.
11. Chairman, East Tennessee Section of the IEEE, 1984-85.
12. Vice President, UTK Chapter of Sigma Xi, 1984-85.
13. President, UTK Chapter of Sigma Xi, 1985-86.
14. Educational Activities Chairman, Tennessee Council of IEEE Region III, 1986-87.
15. General Chairman, IEEE Southeastcon '88, 1985-88.

VIII. OTHER PROFESSIONAL ACTIVITIES

A) Service on National Boards and Committees

1) Consultive panel member, Advanced Fuel Fusion Development Section for DoE Office of Fusion Energy's Technical Planning Activity (TPA) Report (Long-Range Planning Document), 1985-86.

2) Member, National Academy of Sciences-National Research Council's Committee on Aneutronic Fusion-Phase I, 1986-1987.

3) Member, Scientific Advisory Committee to the Air Force Geophysics Laboratory, Hanscom AFB, MA.

4) Member, Fusion Power Working Group at the NASA Lunar Helium-3 Fusion Power Workshop, April 25-26, 1988, Cleveland, OH

B) Consulting

1) Westinghouse Corporation - Consultation on the preparation of their proposal for the EBT-S Prime Contract. April 30, 1980 to December 31, 1980.

2) Tennessee Valley Authority - Was hired to give a series of seven five-hour lectures on fusion energy for the benefit of staff of TVA's Power Office in Chattanooga, Sept. 28 to Nov. 16, 1982.

3) Tennessee Valley Authority - Consultant and Principal Investigator of two closely linked contracts which provided retainer-type consulting and support for one graduate student. January 1, to December 31, 1983.

4) Department of Physics and Astronomy, University of Maryland, College Park, Maryland - Reviewer of proposals submitted to the Air Force Office of Scientific Research (AFOSR), with them acting as intermediary, November 1985 to present.

5) Army Research Office - Consultant and Principal Investigator of a 6-month Short Term Innovative Research contract which supported two GRA's, July 1 to Dec. 31, 1988.

6) BDM Corporation, McLean, VA - Consultant on potential applications of fusion energy to the SDI program, February, 1988 to present.

C) Services as Reviewer

Have served as a reviewer for proposals or manuscripts for the following organizations and journals:

1) Tennessee Valley Authority

2) National Science Foundation, Engineering Directorate

3) Air Force Office of Scientific Research

4) IEEE Transactions on Plasma Science

5) Fusion Technology

6) Plasma Physics and Fusion Energy

7) Nuclear Fusion

8) Aerospace Engineering and Applied Mechanics

9) Journal of Applied Physics

IX. PROFESSIONAL ACCOMPLISHMENTS

In the past twenty years, Dr. Roth has authored or co-authored 110 archival publications, of which 41 were articles in refereed journals, 32 were full-length papers in reviewed conference proceedings, and the remainder of which were internally reviewed NASA reports. Dr. Roth has published in the Physics of Fluids, the Review of Scientific Instruments, the IEEE Transactions on Plasma Science, Physical Review Letters, Plasma Physics, Nuclear Fusion, the Journal of Applied Physics, the Journal of Fusion Energy, the Journal of Nuclear Instruments and Methods, the Journal of Spacecraft and Rockets, Fusion/Technology, the Journal of Mathematical Physics, Nature, and elsewhere. In addition to these publications, Dr. Roth has been author or co-author of 100 oral or poster presentations at professional society meetings, nearly all of which report experimental data on his scientific or engineering work.

While at the NASA Lewis Research Center, Dr. Roth made two pioneering contributions to fusion-related superconducting magnet technology. He was responsible for the basic design and distinctive features of the "Pilot Rig" superconducting magnet facility at NASA Lewis in Cleveland. This facility went into service in December, 1964, and was the first such facility ever to be used for plasma physics or controlled fusion research. Dr. Roth's second contribution in the magnet area was as the engineer responsible for the basic design and distinctive features of the NASA Lewis superconducting bumpy torus magnet facility. This facility went into service in 1972, and was the first superconducting magnet facility anywhere in the world to generate a toroidal magnetic field.

In studying the plasma which these facilities were designed to confine, Dr. Roth discovered two previously unrecognized modes of plasma instability. The first of these is the "continuity-equation oscillation" (the name is Dr. Roth's own) which was observed in the Pilot Rig in 1967. Dr. Roth was the first to investigate this oscillation experimentally, and the first to describe it theoretically. His work on the continuity- equation oscillation has been recognized in standard monographs and compilations such as A. I. Akhiezer et al. Plasma Electrodynamics, and F. Cap's Handbook on Plasma Instabilities, Vol. I. Dr. Roth was also the first to report the experimental observation of the "Geometric Mean Plasma Emission" (Dr. Roth also named this instability). His data were explained theoretically by Professor Igor Alexeff, and they jointly reported the discovery of this new instability in August, 1979.

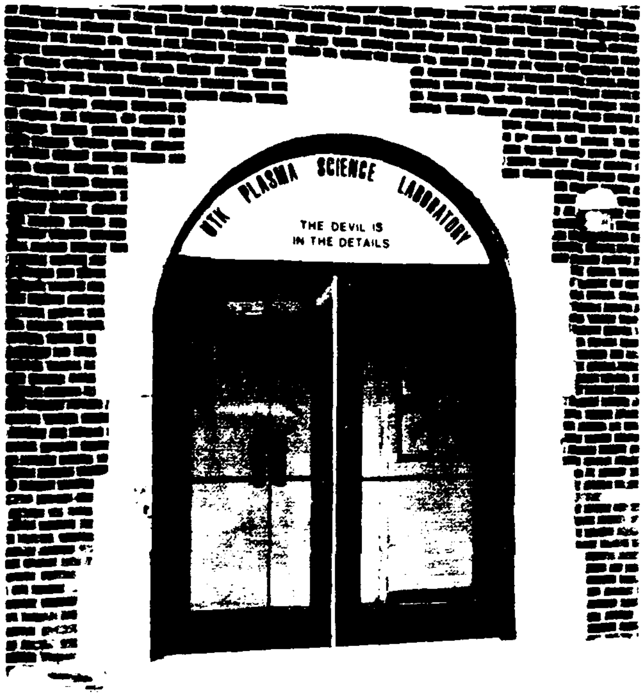
Dr. Roth initiated research on the electric field bumpy torus concept, an approach to creating a plasma of fusion interest in which strong radial electric fields are imposed on a bumpy torus plasma, in such a way that they contribute to the heating, stability, and confinement of the plasma.

Dr. Roth has authoritative knowledge of Penning discharges; the use of superconducting magnet facilities in plasma and fusion applications; the continuity- equation oscillation and moving striations; ion heating and transport in a modified Penning discharge; high temperature plasma physics; fusion energy; and fusion technology. Dr. Roth was the first to identify the physical mechanism responsible for ion heating in a modified Penning discharge, and the first to describe it. Dr. Roth's academic responsibilities have included teaching a required undergraduate course on plasma engineering from his own notes, a one-year senior and graduate level sequence on fusion energy, also from his own notes, a one year graduate course in Plasma Diagnostics which includes a laboratory, a doctoral level course on advanced plasma physics, and intensive one-week minicourses on Fusion Diagnostics and Fusion Energy, which have attracted students from all over the United States and Canada. He has recently published a senior and first year graduate level textbook, "Introduction to Fusion Energy."

APPENDIX B

Study and Research at the UTK Plasma Science Laboratory

Study and Research at the UTK Plasma Science Laboratory



The Plasma Science Laboratory is affiliated with the University of Tennessee's Electrical and Computer Engineering Department on its Knoxville campus. The city of Knoxville is located among the beautiful hills of East Tennessee, and has recently been designated one of the United States' most livable cities. The UTK Campus serves 25,000 students, and provides the cultural and intellectual stimulation of a major university. Within a hundred mile radius of the campus are recreational opportunities unparalleled in the Eastern United States, including the Smoky Mountain and Big South Fork National Parks; numerous state parks; and many TVA lakes, parks, and recreational areas. These provide opportunities for hiking, backpacking, camping, bicycling, fishing, boating, swimming, white water rafting and canoeing, and contact with wilderness areas.

Research at the UTK Plasma Science Laboratory is supervised by Professors J. Reece Roth and Igor Alexeff, both of whom are Fellows of the Institute of Electrical and Electronics Engineers. The research program is funded by contracts from the Department of Energy, the Air Force Office of Scientific Research, and the Office of Naval Research, which provide approximately $300,000 in support annually.

The UTK Plasma Science Laboratory is unusually well equipped for experimental research in steady-state electric field dominated plasmas, and for studying the absorbtion, emission, and interactions of electromagnetic radiation with such plasmas. The Laboratory has an inventory of over $1.5 million in magnet facilities, power supplies, plasma diagnostic equipment, electronic test instruments, microwave components, and RF sources and network analyzers. A significant proportion of this inventory is state-of-the-art equipment of a kind available in few university or national laboratories.

Major facilities available in the UTK Plasma Science Laboratory include a 20 cm bore, 0.35 Tesla water-cooled magnet system; a 17 cm bore, 0.50 Tesla water-cooled magnet system; a 40k VDC, 1.0 ampere power supply; A LeCroy 3500 SA32 transient recorder system; a three-channel, 10 MHz analog-to-digital data handling system; a 1.0 to 26 GHz Integra Panoramic spectrum analyzer; a Hewlett-Packard Model 8510

microwave network analyzer (45 MHz to 18 GHz); and a Hewlett-Packard Model 3577 low frequency network analyzer (5 Hz to 200 MHz). In addition, the following plasma diagnostic systems are available: A conventional and a mass-analyzed charge-exchange neutral energy analyzer; two ½-meter optical spectrometers; a 1½-meter vacuum ultraviolet spectrometer; a 28 GHz polarization diplexing microwave interferometer; a 28 GHz microwave scattering system; a fluctuation-induced transport diagnostic system, including capacitive and Langmuir probes; a computer-assisted retarding potential energy analyzer system; a computer-assisted Langmuir probe system; mass spectrometers; RF signal generators from 1 Hz to 40 GHz; RF spectrum analyzers from 5 Hz to 18 GHz; calibrated, broadband antennas for RF emission measurements in the range of 0.5-1200 MHz; and many other minor probes and devices.

Major areas of research at the UTK Plasma Science Laboratory include exploratory research on electric field dominated plasmas; sub-millimeter microwave devices, including the Orbitron maser; the geometric mean and related interpenetrating beam plasma instabilities; RF emissions and interactions with energetic plasmas; plasma turbulence; anomalous electrical resistivity of electric field dominated plasmas; MHD pumping and power generation using AC; plasma heating by first-order collisional magnetic pumping; and microwave absorbtion resonance spectroscopy of organic and biological materials.

Activities of the UTK Plasma Science Laboratory include contract research; a weekly plasma seminar; experimental research on masters and Ph.D. theses; consulting services by Plasma Lab faculty and staff for local institutions, industry and government; providing state-of-the-art equipment for student training; offering, each summer, the AFOSR - UTK Undergraduate Research Assistantship Program; publishing research results in archival journals; and presenting progress reports on current research at professional society meetings.

The UTK Plasma Science Laboratory is located in Room 101 Ferris Hall and is always available to students for inspection. Part time undergraduate jobs are often available. The Air Force Office of Scientific Research, in cooperation with the Department of Electrical and Computer Engineering, has made available a limited number of undergraduate research assistantships during the summer. These assistantships are for experimental research on AFOSR-sponsored projects. In addition to the above summer undergraduate research assistantship program, graduate research assistantships are available for graduate students interested in pursuing advanced degree work in plasma engineering and fusion energy.

Popularity of the plasma program at UTK is greatest among those students who enjoy building things, and doing hands-on work with actual hardware. Plasma engineering has always appealed to students who wish to do research and development on the leading edge of electrical engineering with technologies that involve the generation and conversion of large amounts of electrical power.

The Electrical and Computer Engineering Department at UTK has offered courses in plasma engineering and fusion energy at the graduate and undergraduate levels for more than 15 years. The ECE Department at UTK is one of very few in the country to offer an undergraduate senior option in plasma engineering. Since 1985, the ECE Department has offered, in addition to graduate instruction in plasma engineering, a graduate-level

option in fusion energy in cooperation with the Nuclear Engineering Department.

The plasma and fusion-related courses offered at UTK by the Departments of Electrical and Computer Engineering (ECE), Nuclear Engineering (NE), and Physics and Astronomy (P) are as follows:

Plasma and Fusion-Related Courses at UTK

1. Introductory Plasma Engineering (offered every year)
   ECE 3190 Plasma I-Plasma Engineering (3)
   ECE 4470 Plasma II-Magnetohydrodynamics (3)
   ECE 4480 Plasma III-Kinetic Theory (3)

2. Introduction to Fusion Energy Sequence (offered every year)
   ECE-NE 4445 High Temperature Plasma Physics (3)
   ECE-NE 4455 Principles of Fusion Reactors (3)
   ECE-NE 4465 Introduction to Fusion Technology (3)

3. Weekly Plasma Seminar (offered every quarter)
   ECE 5990 Plasma Science Seminar (1)

4. Plasma Diagnostics Sequence (offered on even-numbered years only)
   ECE-NE 5315 Plasma Diagnostics I (3)
   ECE-NE 5325 Plasma Diagnostics II (3)
   ECE-NE 5335 Plasma Diagnostics Laboratory (3)

5. Intermediate Fusion Energy Sequence (offered on odd-numbered years only)
   NE-ECE 5815 Fundamentals of Fusion Physics and Engineering (3)
   NE-ECE 5825 Plasma Engineering (3)
   NE-ECE 5835 Fusion Technology (3)

6. Advanced Plasma Physics Sequence (offered as demand warrants)
   ECE-P 6500 High Temperature Plasma Physics I (3)
   ECE-P 6510 High Temperature Plasma Physics II (3)
   ECE-P 6520 High Temperature Plasma Physics III (3)

7. Advanced Fusion Energy Sequence (offered a demand warrants)
   NE 6810 Plasma Engineering II (3)
   NE 6820 Fusion Reactor Design (3)
   NE 6830 Special Topics in Fusion Engineering (3)

All the above courses are available for graduat credit; all students in the ECE plasma progra or affiliated with the UTK Plasma Scienc Laboratory are expected to sign up each quarte for ECE-5990, Plasma Science Seminar.

The UTK campus is shifting from a quarter t a semester schedule in the Fall of 1988. The abov courses will continue to be offered, but with di ferent (3-digit) catalog numbers and with tw rather than three courses in a sequence.

For further information about the UTK Plasm Science Laboratory or the ECE departmenta course offerings, please contact

Professor J. Reece Roth
409 Ferris Hall
University of Tennessee
Knoxville, Tennessee 37996-2100
(615) 974-4446

For a graduate catalog and/or application informa tion, please contact

Director, Office of Graduate
Admissions and Records
218 Student Services Building
University of Tennessee
Knoxville, Tennessee 37996-0220
(615) 974-3251

E01 1340 002-

APPENDIX C

Plasma Science Seminars, 1982-88

5990 EE - PHYSICS PLASMA SEMINAR

Winter Quarter, 1982

Room 405 Ferris Hall
12:00 noon, Fridays

We have asked several outside speakers to come and describe their recent plasma-related work to us. The dates, speakers and approximate topics are as follows:

February 12 - Dr. Owen Eldridge, Fusion Energy Division, ORNL - Current Status of Ion Cyclotron Resonance Heating and recent results from the ORNL EBT-S Experiment.

February 19 - George E. Gorker, Fusion Engineering Design Center, ORNL - Engineering Problems Associated with Handling Large Blocks of Electrical Power for Present and Future Magnetic Fusion Experiments.

February 26 - Philip T. Spampinato, Fusion Engineering Design Center, ORNL - Reference Design and Current Status of the Fusion Engineering Device (FED).

March 5 - Philip Ryan, Fusion Energy Division, ORNL - Status report on his Ph.D. thesis in EE, on the subject of neutral beam development for plasma heating.

Students, faculty and staff are welcome to attend.

5990 EE - PHYSICS PLASMA SEMINAR

Spring Quarter, 1982

Room 405 Ferris Hall
12:00 noon, Fridays

We have asked several outside speakers to come and describe their recent plasma-related work to us. The dates, speakers and approximate topics are as follows:

April 16 -- J. Rand McNally, Jr., Fusion Energy Division, ORNL (retired)
<u>The physics of advanced fuel fusion</u>.

May 7 -- Prof. Edward G. Harris, Department of Physics, UTK
<u>Catastrophe theory as applied to the ELMO Bumpy Torus and other plasmas</u>.

May 28 -- Dr. Vishnu Srivastava, Fusion Engineering Design Center, ORNL. <u>Superconducting magnet technology in the Fusion Engineering Device (FED)</u>.

Students, faculty, and staff are welcome to attend.

PH 5990

Plasma Seminar Schedule Fall 1983

Room 504 Ferris Hall
12:00 Noon, Wednesdays

DATE	SPEAKER AND TOPIC
Sept. 28 -	Prof. Igor Alexeff - Beam-Plasma Instabilities
Oct. 5 -	Mr. Paul Spence - Broadband Antennas
Oct. 12 -	Prof. J. Reece Roth - Scaling Laws for Fusion Reactors
Oct. 14 -	Prof. D Rosenberg - Network Analyzers
Oct. 26 -	Prof. Igor Alexeff - Recent Results in Orbitron Research
Nov. 2 -	Dress Rehearsals for the APS Plasma Physics Divison Meeting
Nov. 9 -	No Plasma Seminar
Nov. 16 -	Trip Report on APS Plasma Physics Division Meeting
Nov. 23 -	Dr. Owen Eldridge, ORNL - Electron Cyclotron Plasma Heating
Nov. 30 -	Mr. Peyman Dehkordi - Operation of the Analog-to-Digital Data Handling System.

All interested persons are invited to attend.

For further information contact

Prof. J. Reece Roth
Dept. of Electrical Engineering
(615) 974-4446

UTK PLASMA SCIENCE SEMINAR SERIES

FALL, 1984

Wednesdays, 9:00 AM 504 Ferris Hall

DATE	
September 26	Profs. Alexeff and Roth, Trip Report on the International Conference on Plasma Physics, Lausanne, Switzerland
October 3	Prof. I. Alexeff, "Recent Progress with the Orbitron Maser"
October 10	Ms. Lisa Hood and Mr. John Clark, UTK Office Of public Relations, "How to Deal with Reporters"
October 17	Prof. J. R. Roth, "Recent Progress with Two Beam Interaction Instabilities"
October 24	Dress Rehearsals for the APS Plasma Physics Division Annual Meeting
October 31	NO SEMINAR - APS MEETING WEEK
November 7	Prof. J. R. Roth, "Plasma Etching for Microelectronics", based on materials provided by J. W. Coburn, IBM
November 14	Mr. William Casson, ORNL, "Far Infrared Scattering on EBT"
November 21	Mr. Phillip Spampinato, Fusion Engineering Design Center, ORNL "Robotics in Fusion Research"
November 28	Prof. J. R. Roth, "How to Get Government Research Contracts"
December 5	Topic to be arranged.

WINTER QUARTER 1985

PLASMA SCIENCE SEMINAR SERIES

Room 504 Ferris Hall
Tuesdays, 9:00-10:15 am

DATE	SPEAKER AND TOPIC
January 15	J. Reece Roth, "How to Obtain Surplus Government Equipment for Experimental Research"
January 24 THURSDAY	Dr. Robert J. Barker, AFOSR, Bolling AFB, Washington, D.C., "Two-and Three-Dimensional Particle-in-Cell Electromagnetic Plasma Simulation".
January 29	Prof. Igor Alexeff, "Recent Results in Orbitron Research"
February 5	Prof. J. Reece Roth, "Plasma Etching fo Microelectronics-II", Based on notes and vue-graphs supplied by J. W. Coburn of IBM.
February 12	Prof. David Rosenberg and Mr. Paul D. Spence, "RF Plasma Emissions Measured with Calibrated, Broadband Antenna".
February 19	Mr. Antonino Carnevali, Fusion Energy Division, ORNL,"Confinement of Beam Ions in the ISX-B Plasma". This willl be a report on Mr. Carnevali's Ph.D. thesis in the Physics Department.
February 26	Dr. Michael J. Gouge, DoE Program Office, Oak Ridge, "Alpha-Driven Currents in Tokamak Reactors". Dr. Gouge will present his recently-completed Ph.D. thesis for the UTK Physics Department.
March 5	Mr. Wlodzimierz (Vlodek) Nakonieczny, "Particle Orbits in the Orbitron Microwave Emitter". This will be a progress report on a Ph.D. Thesis.
March 12	Mr. Mounir Laroussi, "Progress in Theoretical Understanding of Transit-Time Magnetic Pumping and Collisional Plasma Heating".

ALL INTERESTED PERSONS ARE INVITED TO ATTEND

For further information, contact J. Reece Roth, 974-4446

SPRING QUARTER 1985

PLASMA SCIENCE SEMINAR SERIES

Room 504 Ferris Hall
Thursdays, 9:00-10:15 am

DATE	SPEAKER AND TOPIC
April 4	Mr. Gregory Hutchens, University of Illinois, "Group Invariance Properties of the Grad-Shafranov Equation". Mr. Hutchens is a graduate of the UTK Engineering Physics program now studying at Illinois in their Nuclear Engineering Program.
April 11	Prof. Igor Alexeff, "Recent Results from the Orbitron Microwave Emitter at Submillimeter Wavelengths".
April 18	Profs. J. Reece Roth and David Rosenberg, UTK, and Dr. Howard Adler, ORNL, "Interaction of Electromagnetic Radiation with Biological Samples" Joint meeting with the Department of Microbiology and other interested persons to explore research opportunities in this area.
April 25	Mr. Paul Spence, "Measurement of RF Plasma Emissions with Calibrated Antennas", A progress report on Mr. Spence's research program in the UTK Plasma Science Laboratory.
May 2	W. Don Nelson, ORNL Fusion Engineering Design Center, "The Fusion Power Demonstration Study".
May 9	Mr. Fred Dyer, Experimental Technique Associated with Orbitron Microwave Emitters"
May 16	Mr. Mounir Laroussi, "Recent Theoretical Progress on Collisional and Transit-Time Plasma Heating", A progress report on Mr. Laroussi's Ph.D. research program.
May 23	Mr. G. Reza Ghayspoor, "Progress in the Development of a VAX-Assisted Data Handling and Reduction System for Plasma Measurements", A progress report on Mr. Ghayspoor's M.S. thesis research.
May. 30	Dress Rehearsals for poster papers at the IEEE International Conference on Plasma Science, Pittsburgh, PA, June 3-5, 1985.

FALL QUARTER 1985-1986

PLASMA SCIENCE SEMINAR SERIES

EE 5990 - - Section 34482

Room 504 Ferris Hall

Thursdays, 12:00 to 1:15 p.m.

DATE	SPEAKER AND TOPIC
October 3	Prof. Igor Alexeff, A Plasma Wave Oscillator.
October 10	Prof. J. Reece Roth, The Impact of Plasma Heating Efficiency on the Power Balance of Powerplant Fusion Reactors. This is a dress rehearsal for an invited talk and conference paper.
October 17	Paul Spence, Operation of the HP Microwave Network Analyzer, Followed by a hands-on workshop with the instrument in the UTK Plasma Science Laboratory.
October 24	G. Reza Ghayspoor, Development of an Integrated Data Acquisition and Handling System for the Measurement of Radial Transport Rates, Based on Digital Time Series Analysis. This is a M.S.E.E. thesis summary.
October 31	Dress rehearsals of papers for APS Plasma Meeting.
November 7	NO SEMINAR - APS MEETING WEEK
November 14	F. William Wiffen, Metals and Ceramics Division, and Fusion Engineering Design Center, ORNL; Materials Problems and Potential Solutions in Fusion Reactors.
November 21	David Coffey, President, The Nucleus, Inc., How to Start Your Own Small Business.
December 5	John E. Crowley, Low-Noise Measurements of Plasma Turbulence.

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For further information, contact J. Reece Roth, 974-4446

PLASMA SCIENCE SEMINAR SERIES

EE 5990--Section 32437
Room 504 Ferris Hall
Fridays, 12:00 to 1:15 p.m.

DATE	SPEAKER AND TOPIC
January 10	Prof. Igor Alexeff, Department of Electrical Engineering UTK, "Trip Report on the Infrared and Millimeter Wave Conference". This IEEE cosponsored conference was held in December, and many new advances were reported.
January 17	Prof. Karl Audenaerde, Chairman, Engineering Department, State University of New York at New Platz,"Microwave Mode Convertors".
January 24	Prof. J. Reece Roth, Department of Electrical Engineering, UTK, "Transit Time Effects on the Divergence Term of the Plasma Continuity Equations".
January 31	Mr. John E. Crowley, GRA, UTK Plasma Science Laboratory, Low-Noise Measurements for Plasma Turbulence Research". This status report will cover Mr. Crowley's Master's thesis research in the UTK Plasma Lab.
February 7	Mr. G. Reza Ghayspoor, GRA, UTK Plasma Science Laboratory, "Extension of the LeCroy Transient Recorder System to Three Simultaneous Channels". This is an updating of Mr. Ghayspoor's recent Master's degree.
February 14	Mr. Mounir Laroussi, GRA, UTK Plasma Science Laboratory, "First-Order Plasma Heating Using Collisional Magnetic Pumping". This status report will describe the theoretical aspects of Mr. Laroussi's Ph.D. thesis.
February 21	Prof. J. Reece Roth, Department of Electrical Engineering, UTK, "How to Write a Textbook". Useful hints on writing a textbook in the word-processor era and some interesting aspects of the book publishing business will be discussed.
February 28	Prof. Marshall Pace, Department of Electrical Engineering, UTK, "Research at UTK on the Initiation of Dielectric Breakdown". Prof. Pace will describe some research underway at UTK in this area.
March 7	Prof. J. Reece Roth, Department of Electrical Engineering, UTK, "Theoretical and Experimental aspects of the Plasma Continuity Equation Oscillation". This will describe a plasma instability first discovered experimentally and described theoretically by Prof. Roth.
Ma h 14	Dr. Robert W. Schumacher, Hughes Research Laboratories, Malibu, California, "Microwave Tube Research at the Hughes Research Laboratories". Dr. Schumacher will discuss the Hughes research program in this area, including their work on the Orbitron maser.

ALL INTERESTED PERSONS ARE INVITED TO ATTEND

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WINTER QUARTER, 1986

PLASMA SCIENCE SEMINAR SERIES

Spring, 1986

EE 5990--Section 33236
Room 504 Ferris Hall
Fridays, 12:00 to 1:15 pm

Date	SPEAKER AND TOPIC
April 4	Organization meeting and dress rehearsals for the 1986 SSST Plasma Papers
April 11	Prof. Igor Alexeff, Department of Electrical Engineering, UTK "Recent Progress in Orbitron Research".
April 18	Mr. John B. Miller, Fusion Engineering Design Center, ORNL, "Prevention of the Current-Quench Phase of a Major Disruption in a Tokamak Reactor" This plasma engineering study is Mr. Miller's Ph.D. Thesis in Nuclear Engineering.
April 25	Mr. Tim Bigelow, Fusion Energy Division, ORNL, "A Survey of Plasma RF Heating Experiments in Japan". A report of his recent trip to Japanese Fusion Labs.
May 2	Profs. J. Reece Roth and Igor Alexeff, Dept. of Electrical Engineering, UTK. "A Study of Tokamak Confinement Time Scaling Based on MHD Current Penetration". A derivation of an alcator-like confinement time scaling from first principles.
May 9	Mr. John E. Crowley, GRA, UTK Plasma Science Laboratory, "Conversion of the HP 3577A Network Analyzer to a Low Noise Spectrum Analyzer Mode of Operation". This seminar will double as Mr. Crowley's oral exam on his M.S. Thesis.
May 16	Mr. Phil Ryan, Fusion Energy Division, ORNL, and UTK Ph.D. candidate, "Analysis and Design of an Energy Recovery System for a Space Charge Neutralized Ion Beam". A summary of Mr. Ryan's Ph.D. Thesis.
May 23	Prof. J. Reece Roth, Department of Electrical Engineering, UTK, "Trip Report on the 13th IEEE International Conference on Plasma Science, Sakatoon, Canada," and "Langevin Formalism for Absorbtion of RF Power at Gyroresonance"
May 30	Mr. Paul Spence, GRA, UTK Plasma Science Laboratory, "Measuring Collision Frequencies by Microwave Absorbtion"

ALL INTERESTED PERSONS ARE INVITED TO ATTEND

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PLASMA SCIENCE SEMINAR SERIES

Fall Quarter, 1986

ECE 5990--Section 34067
Room 504 Ferris Hall
Fridays, 12:00 to 1:15 p.m.

DATE	SPEAKER AND TOPIC
September 26	ORGANIZATION MEETING - Prof. J. Reece Roth, UTK: "Trip Report on the Gordon Conference on Plasma Chemistry"; and Prof. Igor Alexeff, UTK: "Survey of Off-Campus Orbitron Research"
October 3	Prof. Igor Alexeff, ECE Dept., UTK: "Recent Progress on Orbitron and MHD Research at UTK".
October 10	Mr. John E. Crowley, GRA, UTK Plasma Science Laboratory: "Experimental Performance of the HP 3577A Two-Channel Conversion System".
October 17	Prof. J. Reece Roth, ECE Dept., UTK: "Research Opportunities in the Interaction of Electromagnetic Radiation with Biological Samples".
October 24	Mr. Mounir Laroussi, GRA, UTK Plasma Science Laboratory: "Computer Simulation of Plasma Heating by Collisional Magnetic Pumping".
October 31	Dress rehearsals for the APS meeting.
November 7	No seminar this week - APS Plasma Physics Division Meeting in Baltimore, MD.
November 14	Mr. Paul Spence, GRA, UTK Plasma Science Laboratory: "Recent Results of Experimental Turbulence Research".
November 21	Mr. Alan L. Wintenberg, GRA, UTK ECE Department: "Pre-Breakdown Studies in Liquid Dielectrics".
December 5	Mr. Mark Rader, GRA, UTK Plasma Science Laboratory: "Recent Progress on the Steady-State Orbitron Microwave Emitter".

ALL INTERESTED PERSONS ARE INVITED TO ATTEND

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PLASMA SCIENCE SEMINAR SERIES

Winter Quarter, 1987

ECE 5990--Section 32423
Room 504 Ferris Hall
Fridays, 1:00 to 2:15 p.m.

DATE	SPEAKER AND TOPIC
January 9	Prof. J. Reece Roth, UTK: "Recent Developments in Aneutronic Fusion for DoD Space Power and Propulsion Systems." A scout report from Washington on recent DoD interest in fusion energy.
January 16	Mr. Gregory Hutchens, Univ. of Illinois: "Nuclear Reactor Kinetics and Fusion Reactors" Mr. Hutchens is a former student, B.S. in Engineering Physics, who will report on his doctoral research at Illinois.
January 23	Prof. Igor Alexeff, UTK: "How to Start Your Own Company: Innovation and Venture Capital" Prof. Alexeff will draw on his experiences as founder and first President of the Tennessee Inventor's Association.
January 30	Prof. J. Reece Roth, UTK: "Theory of Plasma Ion Implantation for Hardening Metals". This will describe the plasma conditions required to achieve a given level of ion implantation in complex metal objects, and how to calculate exposure times, energy requirements, and other commercially significant factors in the application of this new process.
February 6	Prof. Igor Alexeff, UTK: "A New Theory of Dielectric Breakdown in Liquids". This will discuss a new theory developed from experimental data taken in Prof. Marshall Pace's Laboratory.
February 13	Paul N. Haubenreich, Fusion Energy Division ORNL: "Superconducting Magnets for Fusion Confinement", A survey of superconducting magnet technology and a progress report on ORNL's impressive Large Coil Program.
February 20	Mr. Mounir Laroussi, GRA, UTK Plasma Science Laboratory: "Theoretical and Computational Results for Collisional Magnetic Pumping". This will summarize the theoretical portion of Mr. Laroussi's Ph.D. Thesis, and contain a progress report on his experimental research.
February 27	Dr. Joseph C. Danko, Director, UTK Center for Materials Processing: "Plasma Processing of Materials". Prof. Danko will discuss some large-scale commercial applications of plasmas and some promising new plasma-based materials processing methods.
March 6	David W. Swain, Fusion Energy Division, ORNL: "Research and Development on Radio Frequency Power at ORNL". A survey of high power RF technology and applications at ORNL.
March 13	Prof. Igor Alexeff, UTK; and Mr. Mark Rader, GRA, UTK Plasma Science Laboratory: "Recent Advances in Orbitron Development and in Microwave Technique". This will summarize interesting recent developments in these areas.

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PLASMA SCIENCE SEMINAR SERIES

Spring Quarter, 1987

ECE 5990--Section 31628
Room 504 Ferris Hall
Fridays, 12:00 to 1:15 p.m.

DATE	SPEAKER AND TOPIC
April 3	Mr. Ali Keshavarzei, Senior, ECE Department, UTK: "Low Frequency Continuity-Equation Oscillations In Partially Ionized Gases". This will be a dress rehearsal for Mr. Keshavarzi's appearance in the final round of the Region III IEEE Student Paper Competition at Southeastcon '87 in Tampa.
April 10	Prof. J. Reece Roth, UTK ECE Department: "How to write Architect's Guidelines for Scientific Research Workspace". This is something that nearly everyone does once or twice in their careers, and may be useful to some in connection with the future Science/Engineering/Computer (SEC) Research Building.
April 24	Mr. John C. Mannone, UTK Department of Physics and Astronomy: "Modeling of Electron Transport in Dielectric Fluids Subject to High Electric Fields". This will consist of a report on an electrohydrodynamic (EHD) experiment performed in the UTK Plasma Science Laboratory.
May 1	Prof. Igor Alexeff, UTK ECE Department: Advances in High Voltage Beakdown in Liquids". This will summarize theoretical progress made in joint collaboration with Prof. Marshall Pace's research group.
May 8	Mr. Mark Rader, GRA, UTK Plasma Science Laboratory, "How to Use the Presentation Graphics Package on the Plasma Lab's HP 9836 Computer".
May 15	Mr. Mounir Laroussi, GRA, UTK Plasma Science Laboratory, "Recent Results from Experiments with the Collisional Magnetic Heating of Plasmas". This will describe recent research results and also contain a trip report on the APS Topical Meeting on the RF Heating of Plasmas.
May 22	Prof. J. Reece Roth, UTK ECE Department: "How to Organize a Technical Conference". This is something that one gets stuck with sooner or later, so you might find it useful to know what mistakes to avoid.
May 29	Mr. Paul D. Spence, GRA, UTK Plasma Science Laboratory, "Recent Results from Experiments wth Plasma Turbulence". A progress report on Paul's Ph.D. thesis, now in its final stages.

ALL INTERESTED PERSONS ARE INVITED TO ATTEND
For further information, contact J. Reece Roth, 974-4446

PLASMA SCIENCE SEMINAR SERIES

Fall Quarter, 1987

ECE 5990--Section 33945
Room 504 Ferris Hall
Fridays, 12:00 to 1:00 p.m.

DATE	SPEAKER AND TOPIC
September 26	Organization Meeting - Prof. J. Reece Roth, UTK: "Trip Report on the 18th International Conference on Phenomena in Ionized Gases, Swansea, Wales". Slides and a summary of recent advances.
October 2	Prof. Igor Alexeff, UTK: "Trip Report on the International Conference on High Power Microwave Sources, Chengdu, China." Slides of the conference and the fusion research institute.
October 9	Prof. J. Reece Roth, UTK: "Space Applications of Fusion Energy." Preview of a paper at the 12th Symposium on Fusion Engineering.
October 16	Prof. Alexeff, UTK: "Advanced Orbitron Developments." Recent results of orbitron Research in the UTK Plasma Science Laboratory.
October 23	Mr. Tom E. Shannon, Manager, Fusion Engineering Design Center, ORNL: "Status of the Compact Ignition Tokamak (CIT) Project." This talk will describe the proposed step in DT Tokamak Research beyond the TFTR experiment.
October 30	Prof. Igor Alexeff and J. Reece Roth, UTK; and Mr. Fred Dyer, Mark Rader, Paul Spence and Mounir Laroussi, GRAs, UTK Plasma Science Laboratory: "Dress Rehearsal for APS Annual Meeting of the Plasma Physics Division." An overview and progress report on recent work done in the plasma lab.
November 6	APS Plasma Physics Division - No seminar this week
November 13	Prof. J. Reece Roth, UTK: "Trip Report on the 8th International Conference on Plasma Chemistry, Tokyo, Japan." Report on recent advances in plasma-assisted diamond deposition, thermal plasmas, and plasma torches, with slides of the conference, plasma equipment exhibitors, and major Japanese fusion facilities.
November 20	Dr. Antonino Carnevalli, RPI and Fusion Energy Division, ORNL: "Heavy Ion Beam Probing - Measurement of Plasma Potential and Turbulent Transport." Dr. Carnevalli is a former UTK student who is now working on the ATF Experiment at ORNL.
November 27	Thanksgiving Holiday
December 4	Mr. Scott Stafford and Mr. Min Wu, GRAs, UTK Plasma Science Laboratory. "Proposed Masters Thesis Research."

ALL INTERESTED PERSONS ARE INVITED TO ATTEND

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PLASMA SCIENCE SEMINAR SERIES

Winter Quarter, 1988

ECE 5990--Section 33743

Room 504 Ferris Hall

Fridays, 12:05 to 12:55 p.m.

DATE	SPEAKER AND TOPIC
January 8	UTK closed due to bad weather
January 15	Organization meeting, including viewing of a 20-minute video tape, "Nuclear Engineering and Plasma Physics Research at the University of Washington, Seattle".
January 22	Prof. Igor Alexeff, ECE Dept., UTK, "Trip Report on the Conference on Infrared and Millimeter Waves". Many interesting recent advances were reported at this meeting, including our own Orbitron work.
January 29	Prof. J. Reece Roth, ECE Dept., UTK, "Recent Developments in the Treatment of Heart Disease", The only warning that half the victims of heart disease have is death. Prof. Roth will present a layman's summary of recent developments in risk factors, methods of treatment, and thresholds for action.
February 5	Mr. Frank Davis, ORNL, "Remote Maintenance of the Compact Ignition Torus (CIT)". Mr. Davis is responsible for developing the robotic manipulators used to deal with radio-activated components from this fusion reactor.
February 12	Prof. Mark Kot, UTK Mathematics Dept., "Routes to Chaos". This will be a tutorial on the development of chaotic behavior from deterministic, nonlinear systems such as plasma turbulence.
February 19	Mr. Mounir Laroussi, UTK Plasma Science Laboratory, "Recent Experimental Results from Collisional Magnetic Pumping Research", A semifinal report on Mounir's Ph.D. thesis research.
February 26	Mr. Paul D. Spence, UTK Plasma Science Laboratory, "Research on Plasma Instabilities and Turbulence", A semi-final report on Paul's Ph.D. thesis research.
March 4	Mr. Scott Stafford and Mr. Min Wu, UTK Plasma Science Laboratory, "Progress Reports on Master's thesis research in the UTK Plasma Science Laboratory"

ALL INTERESTED PERSONS ARE INVITED TO ATTEND

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PLASMA SCIENCE SEMINAR SERIES

Spring Quarter, 1988

ECE 5990--Section 33127
Room 504 Ferris Hall
Fridays, 12:05 to 1:00 p.m.

DATE	SPEAKER AND TOPIC
March 5	Organization Meeting. Also, Prof. J. Reece Roth, UTK, "Survey of Plasma Science". This talk will cover the many engineering and industrial applications of Plasma Physics. An extensive topical outline will be distributed.
April 1	No Seminar - University Holiday
April 8	Prof. Igor Alexeff, UTK, "Recent Developments in the Orbitron MASER". This will be a dress rehearsal of Prof. Alexeff's invited paper at the IEEE Southeastcon '88 meeting.
April 15	Mr. Alan Wintenberg, GRA, UTK Department of Electrical and Computer Engineering, "Recent Research in Liquid Dielectrics at UTK". This is a progress report on some interesting discoveries recently made at UTK on pre-breakdown phenomena.
April 22	Dr. James F. Lyon, ORNL Fusion Energy Division: "The ORNL Advanced Toroidal Facility (ATF) and Its Relation to the World Stellarator Program" this will include a description and preliminary results from ORNL's newest fusion experiment.
April 29	Prof. Mark Kot, UTK Department of Mathematics, "Routes to Chaos - II". This will be a continuation of Prof. Kot's lecture last quarter on the theory of chaos as it may apply to plasmas.
May 6	Dr. Michael J. Gouge, ORNL Fusion Energy Division, "Pellet Injection for Fusion-Related Plasmas". This talk will describe the outstanding work at ORNL on refueling fusion plasmas by accelerating pellets of hydrogen ice to speeds faster than a bullet.
May 13	Prof. J. Reece Roth, UTK, "Recent Developments in Plasma Chemistry and in Mining ^{3}He from the Lunar Surface". This talk will summarize two recent workshops on these very different subjects.
May 20	Mr. Mounir Laroussi, GRA, UTK Plasma Science Laboratory, "Plasma Heating by Collisional Magnetic Pumping". This will be a final report on the theoretical and experimental aspects of Mounir's Ph.D. thesis.
May 27	Mr. Mark S. Rader GRA, UTK Plasma Science Laboratory, "Development of the First Steady-State Orbitron". This will be a presentation of Mark's Masters Thesis research.

ALL INTERESTED PERSONS ARE INVITED TO ATTEND

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PLASMA SCIENCE SEMINAR SERIES

Fall Semester, 1988

ECE 495--Section 33252
ECE 598--Section 33430

Room 504 Ferris Hall
Fridays, 12:20 to 1:10 p.m.

DATE	SPEAKER AND TOPIC
August 26	ORGANIZATION MEETING - Prof. J. Reece Roth, UTK: "A Survey of Plasma Science" This lecture will review some of the industrial uses of this rapidly developing field, and show slides of some industrial exhibitors at a recent international conference on plasma chemistry.
September 2	Prof. J. Reece Roth, UTK: "Mysteries of Plasma Physics: Part I-Ball Lightning". This lecture is the first in a series designed to explore some classic unsolved problems in plasma physics. Some physical mechanisms for ball lightning will be explored in light of available observations, and their possible relevance to weapons and fusion energy will be discussed.
September 9	Prof. Igor Alexeff, UTK: "Recent Progress on the Orbitron Submillimeter Microwave Maser and on Related Devices". Prof. Alexeff, who holds the basic patent on the Orbitron tube, will describe some recent advances made in the UTK Plasma Science Laboratory.
September 16	Prof. J. Reece Roth, UTK: "How and Where to Publish Scientific Papers". This talk will review the procedure followed to organize, write, and publish scientific papers in the archival literature. New information on the relative cost of publication and readership of various plasma journals will be presented.
September 23	Prof. Igor Alexeff, UTK: "Trip Report on Recent Microwave Tube Conferences". Prof. Alexeff will report on some exciting new developments in the subjects of high frequency and high power microwave power production.
September 30	Prof. J. Reece Roth, UTK: "Mysteries of Plasma Physics: Part II - Confinement Time Scaling in Tokamaks". This lecture is the second in a series on classic unsolved problems in plasma physics. After 35 years of fusion research, the mechanism by which particles get from the inside to the outside of tokamaks has not yet been identified. Some phenomenological scaling laws, unsuccessful theories, and possible models will be discussed.
October 7	Prof. J. Reece Roth, UTK: "Space Applications of Fusion Energy". This will be a dress rehearsal for the 8th ANS Topical Meeting on the Technology of Fusion Energy, October 9-13, 1988.

October 14	Mr. Scott Painter, ORNL: "Alpha Particle Losses from Compact Torsatrons". This talk will be a progress report on Mr. Painter's Ph.D. thesis for the UTK Nuclear Engineering Department.
October 21	Mr. Min Wu, GRA, UTK Plasma Science Laboratory: "Experimental Research on Plasma Heating by Collisional Magnetic Pumping". This will be a report on Mr. Wu's Master's thesis.
October 28	Dress rehearsal of papers for the APS Plasma Physics Division Meeting.
November 4	No meeting this week-APS Plasma conference.
November 11	Profs. Igor Alexeff and Marshall Pace, and Mr. Alan Wintenberg, UTK: "Recent Progress in Understanding Electrical Breakdown in Dielectric Fluids". This will describe research done under a DoE contract here in Ferris Hall.
November 18	Mr. Scott Stafford, GRA, UTK Plasma Science Laboratory: "Application of Chaos Theory to Experimental Plasma Turbulence". This will be a report on Mr. Stafford's Master's thesis
December 2	Mr. Thomas E. Shannon, ORNL: "Design and Cost Evaluation of a Generic Magnetic Fusion Reactor Using the DD Fuel Cycle". This talk will outline the highpoints of Mr. Shannon's Ph.D. thesis for the Engineering Science and Mechanics Department at UTK.

ALL INTERESTED PERSONS ARE INVITED TO ATTEND

For further information, contact J. Reece Roth, 974-4446

APPENDIX D

Bibliography of Archival Papers Supported by Contracts ONR N00014-80-C-0063 and N00014-88-K-0174

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APPENDIX E

Text of Archival Papers Supported by
Contracts ONR N00014-80-C-0063
and N00014-88-K-0174

APPENDIX E

Text of Archival Papers Supported by
Contracts ONR N00014-80-C-0063
and N00014-88-K-0174

Electromagnetic emission and anomalous resistivity from equal and oppositely directed electron beams

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Raghuveer Mallavarpu

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The experimental observation and theoretical description of a previously unrecognized mechanism for generating electromagnetic emissions and anomalous resistivity from a beam-plasma interaction which is characteristic of Penning discharges is reported. Very clear emissions were observed from electric field-dominated bumpy torus plasma near the geometric mean plasma frequency. These emissions are inconsistent with familiar physical mechanisms, and occurred in excellent agreement with the theoretical frequency $\omega_{gm} = 0.537(\omega_{pe}\omega_{pi})^{1/2}$. This frequency was derived from a theory based on the interaction of two opposite, interpenetrating electron beams with a heavy ion plasma. The anomalous resistivity associated with this interaction is predicted to several hundred times that of the familiar Buneman or "turbulent" resistivity. A perturbation procedure is used to obtain analytic expressions for the emission frequency and the anomalous resistivity in the zero temperature case. These results are extended to include the effects of finite ion temperatures on the dispersive properties of the plasma.

I. INTRODUCTION

There exist several well-known mechanisms for the generation of microwave power from beam-plasma interactions.[1-4] In this paper we report the experimental observation and theoretical description of a previously unrecognized mechanism for generating anomalous resistivity and electromagnetic emissions from equal and oppositely directed electron beams interacting with heavy background ions. Our approach is both experimental and analytical. The electromagnetic emissions considered in this paper were first observed experimentally.[5] In the theoretical portion of this paper, a perturbation procedure is applied to the appropriate dispersion relation. The frequency, growth rate, and effective conductivity resulting from this beam-plasma interaction are obtained as closed form, analytical expressions. The dispersive properties of this emission mechanism are obtained in the cold ion and finite ion temperature limits.

The beam-plasma interaction mechanism considered in this paper is generated by two equal, oppositely directed electron beams interacting with heavy background ions. The emission frequency and effective conductivity differ significantly in absolute magnitude, and functional dependence on ion mass, from more familiar beam-plasma interaction mechanisms, such as the single electron beam interacting with a heavy ion background discussed by Buneman[6]; the single or double electron beams (parallel, traveling in the same direction) interacting with a plasma, which was originally discussed by Pierce[7-9] and Haeff,[10] and which forms the basis for the operation of traveling wave tubes; the two opposite and interpenetrating electron beams interacting with a background of stationary cold electrons, which has been discussed by Cuperman *et al.*[11,12]; and the case of equal and interpenetrating ion beams interacting with a cold, stationary, electron plasma which has been considered by Davidson[3] and Krall and Trivelpiece.[4]

It apparently has not been previously recognized that the dispersion relation describing the interaction of two equal and oppositely directed electron beams interacting with a background of heavy ions has a narrow window in the vicinity of $kv \approx \omega_{pe}$, for which complex solutions with real frequencies and positive growth rates occur. The frequency and growth rates of growing (emitting) waves are obtained theoretically by a perturbation procedure. The real part of the frequency is shown to be consistent with electromagnetic emissions which were observed during a series of experiments on the National Aeronautics and Space Administration's NASA-Lewis bumpy torus plasma.[5] A preliminary report on the theoretical and experimental aspects of the emission, but not the conductivity or finite temperature effects, has been published previously.[13] The frequency of what we call the "geometric mean plasma emission" is located near the geometric mean of the ion and electron plasma frequency. The effective conductivity resulting from the interaction of the two equal and interpenetrating electron beams is typically several hundred times lower than the anomalous or "turbulent" conductivity derived from the Buneman mechanism.[14]

The organization of this paper is based on the historical order in which the information about this emission was obtained. In Sec. II we report the experimental observation of the geometric mean plasma emission. The experimental apparatus in which it was observed is described, the nature of the raw data is illustrated and the functional dependence of the emission frequency on electron number density and magnetic field strength are shown. In Sec. III, a theoretical description of the geometric mean plasma emission is presented. The appropriate zero temperature dispersion relation for the case of two equal and interpenetrating electron beams in a background of heavy ions is set up, the real fre-

quency and growth rate are obtained by a perturbation procedure, finite ion temperature effects are included in the dispersion relation, and their effects on the frequency and growth rate are determined. Finally, the effective plasma conductivity is calculated for this beam-plasma interaction. In Sec. IV, we compare the frequency and effective conductivity resulting from this interaction mechanism with that of other beam-plasma interaction mechanisms. We discuss some quantitative considerations, since it appears that the effective conductivity resulting from this form of beam-plasma interaction is lower than that of any other known beam-plasma interaction mechanism. We also suggest some possible manifestations of this emission, including geophysics, Penning discharges, and turbulent heating.

II. EXPERIMENTAL OBSERVATIONS

A. Experimental apparatus

The microwave radiation experiments described in this paper were conducted on the National Aeronautics and Space Administration's NASA–Lewis bumpy torus, a machine that operates in the steady state under the influence of a dc toroidal magnetic field and strong dc electric fields along the minor radius of the plasma.[15-17] The electric fields heat the ions preferentially by $(E\times B)/B^2$ drift, and are a major factor in determining the plasma stability and confinement properties.[17,18] Gross confinement is provided by the bumpy torus magnetic field generated by 12 superconducting coils.

In these experiments, the plasma was generated by biasing the midplane electrode rings to positive potentials with respect to the grounded coils[15,16] (see Fig. 1). Under these conditions, the plasma resembles twelve modified Penning discharges[19] in a toroidal array. The strong magnetic field restricts electron motion across field lines in the direction of the positive electrode ring at the midplane. As in all Penning discharges, the electron motion in the axial direction is dominated by their presence in an electrostatic potential well; parallel fields cause the electrons to oscillate back and forth through the midplane, at which point their parallel velocity is highest. Since the electrons are traveling in both (opposite) directions at the midplane, their distribution approximates two interpenetrating beams. The electron population is constantly replenished by additional electrons which are created by ionization and fall down the axial potential well. The two interpenetrating beam distribution function will be maintained in the face of instabilities which would otherwise thermalize the midplane axial velocity.

The detection system used to detect microwave radiation from the plasma consists of a 1.5 m long, 50 Ω minature coaxial line, one end of which is suitably shaped in the form of a straight wire antenna. The antenna is concentrically located in a re-entrant quartz tube that is inserted into the vacuum tank through an airlock. The other end of the coaxial line leads to a spectrum analyzer capable of scanning the range 10 MHz to 18 GHz. The wavelength of the radiation detected in this investigation is much longer than the probe dimension, so the probe is acting as a near-field detector of the electric field of the wave. The emissions have recently been observed several wavelengths from a Penning discharge plasma, where they can interfere with reception in the FM radio band.

Figure 1 shows the location of the rf probe with respect to the electrode ring, coil Dewars, and the toroidal axis of the plasma. Lines of constant magnetic field strength are superimposed on the figure. The magnetic field in the vicinity of the probe tip at its closest approach to the plasma is 20% of B_{max}. The maximum magnetic field on the coil axis was $B_{max}=2.4$ T for the data taken at constant magnetic field. The magnetic contour lines shown in Fig. 1 are at increments of 5% of B_{max}.

B. A novel plasma emission

Previous studies of the electromagnetic emission spectrum from this plasma revealed broad peaks in the vicinity of the lower hybrid frequency,[16] and near the electron plasma frequency.[5] Very clear emissions were also observed at a frequency which is inconsistent with familiar mechanisms of plasma emission.

Figure 2 shows the emission spectrum from 0 to 100 MHz at three distances of the antenna from the plasma

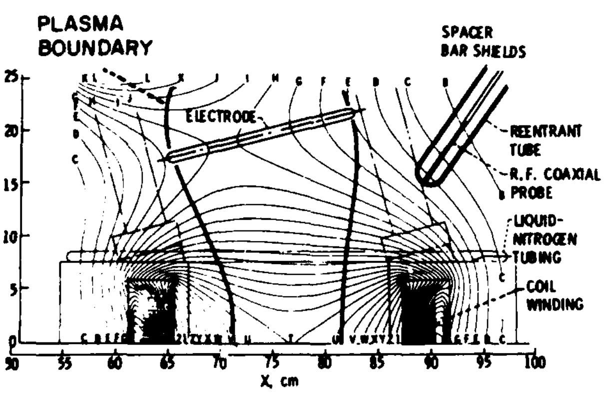

FIG. 1. Location of the rf probe with respect to the midplane electrode ring, coil Dewars, the approximate plasma boundary, and the toroidal axis of the plasma. The magnetic field at the probe tip at its closest approach is 20% of B_{max}.

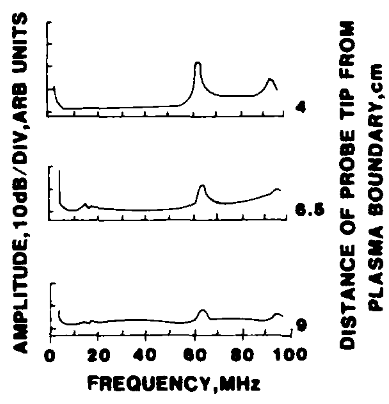

FIG. 2. Spectrum of rf emissions as a function of distance from the plasma boundary. The peak at 65 MHz is the geometric mean plasma emission. Shown are tracings from the original oscillographs.

E-2

boundary. The peak at 65 MHz is the new mode of emission discussed in this paper. The radiation appeared as a narrow peak that shifted in frequency as the plasma parameters were varied. The amplitude of the rf emission was seen to depend on the distance of the coaxial antenna from the plasma boundary, becoming greatest for the closest approach of the probe to the plasma.

The emission was found to increase in frequency as the plasma density was increased from $5\times10^9/\mathrm{cm}^3$ to $2\times10^{11}/\mathrm{cm}^3$. The experimental data are shown in Fig. 3(a), in which the observed emission frequency is plotted against the average electron number density measured with a microwave interferometer. For these conditions, the toroidal magnetic field under the mirror coils was $B_{max}=2.4$ T, and the background gas pressure was 7.4×10^{-5} Torr of deuterium. The emission frequency was observed to have a square root dependence on electron number density (the straight lines have a slope of 1/2), but its absolute magnitude was far too low to be consistent with the electron plasma frequency, and far too high to be consistent with the ion plasma (or lower hybrid) frequency.

To determine whether this emission was related to a hybrid or cyclotron frequency, the plasma density was kept constant at $n_e=5.8\times10^{10}/\mathrm{cm}^3$, while the magnetic field was varied. The results, over more than a factor of 2 in the magnetic field, are shown in Fig. 3(b).

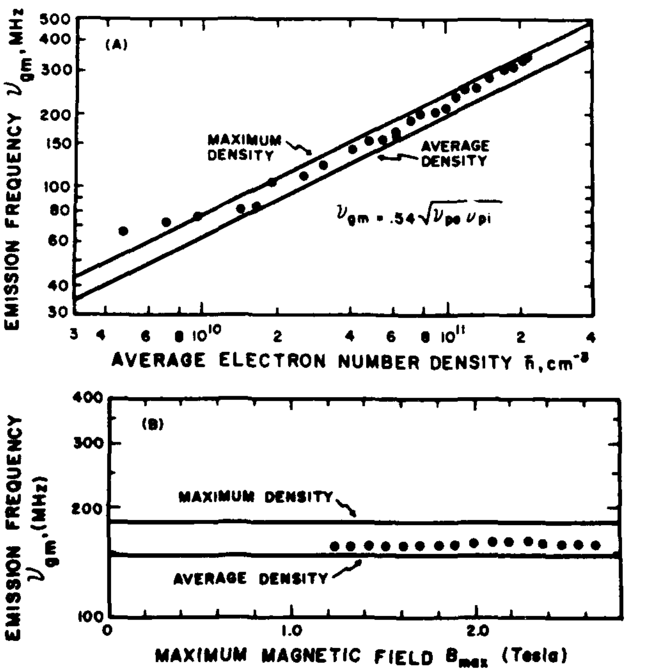

FIG. 3. Functional dependence of emission frequency on plasma parameters. (a) The observed emission frequency as a function of the average electron number density. The lower line is the theoretical expression of Eq. (14) based on the average electron number density; the upper line is based on the maximum density on the plasma axis. (b) The observed emission frequency as a function of the maximum magnetic field. The average electron number density was held constant at $5.8\times10^{10}/\mathrm{cm}^3$, and the background deuterium density was $2.6\times10^{12}/\mathrm{cm}^3$. The theoretical values are given by Eq. (14) as in Fig. 3(a).

These data are consistent with no dependence upon magnetic field strength.

III. THEORETICAL DESCRIPTION

A. The interpenetrating beam interaction

In interpreting our results, we assume that the bumpy toroidal plasma with positive bias acts like a toroidal array of Penning discharges end-to-end with equal and interpenetrating beams of electrons in each acting on a background of plasma ions, as illustrated schematically in Fig. 4. This is a situation which may arise in Penning discharges,[19,20] in the magnetosphere, and in toroidal containment devices with no net toroidal current. For the zero temperature case, the distribution functions of ions and electrons are delta functions, with the stationary ions having twice the density of the two interpenetrating electron beams. As the ions acquire a finite temperature, the width of the ion distribution function will increase.

B. The zero temperature dispersion relation

The dispersion relation appropriate for this interpenetrating beam interaction has been given by Briggs[2] and Cap.[1] For oscillations parallel to B it is given by

$$D(\omega) \equiv \frac{\frac{1}{2}\omega_{pe}^2}{(\omega-kv)^2} + \frac{\frac{1}{2}\omega_{pe}^2}{(\omega+kv)^2} + \frac{\omega_{pi}^2}{\omega^2} = 1\,. \tag{1}$$

It is assumed that each electron beam comprises half of the total electron population, and that the beam electrons and the stationary, cold ions together constitute a quasi-neutral plasma such that the following relation between the beam, electron, and ion number densities holds

$$n_B = \tfrac{1}{2}n_e = \tfrac{1}{2}n_i\,. \tag{2}$$

The electron and ion plasma frequencies may be written as

$$\omega_{pe}^2 = n_e e^2/m\epsilon_0\,, \tag{3a}$$

$$\omega_{pi}^2 = n_i Z^2 e^2/\epsilon_0 M\,, \tag{3b}$$

where m is the electron mass, and M is the ion mass. A dimensionless frequency and wave number are defined as

$$y = \omega/\omega_{pe}\,, \tag{4a}$$

$$x = kv/\omega_{pe}\,, \tag{4b}$$

where a dimensionless parameter ϵ is defined as

$$\epsilon \equiv \omega_{pi}^2/\omega_{pe}^2 = m/M = 1/1836A\,, \tag{5}$$

and for the present analysis is just the ratio of electron

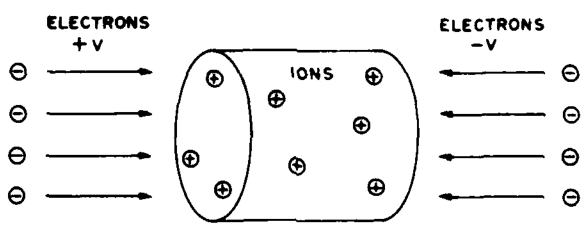

FIG. 4. Simplified model of emitting plasma.

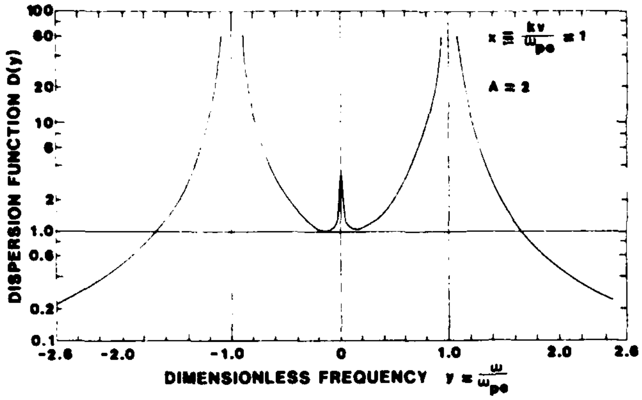

FIG. 5. The dispersion function $D(y)$ from Eq. (6) as a function of dimensionless frequency $y=\omega/\omega_{pe}$ for conditions yielding a complex frequency with finite real and imaginary parts. The dimensionless wavenumber $x=kv/\omega_{pe}=1$, with deuterium background ions.

and ion masses, a very small number which makes possible a perturbation analysis. The parameter A is the atomic mass number of the species in question.

By substituting the definitions in Eqs. (2) through (5) into Eq. (1), one may obtain the dispersion function in dimensionless form as

$$D(y)=\frac{\frac{1}{2}}{(y-x)^2}+\frac{\frac{1}{2}}{(y+x)^2}+\frac{\epsilon}{y^2}=1\,,$$

or

$$D(y)=(x^2+y^2)/(y^2-x^2)^2+\epsilon/y^2=1\,. \tag{6}$$

The dispersion function $D(y)$ of Eq. (6) is plotted in Fig. 5 against the dimensionless frequency y for the parameters $x=1.0$, and a "deuterium" ϵ, equal to 1/3672, with $A=2.0$. There are two resonant solutions above ω_{pe}, at $y=\pm 1.72$, and four complex solutions (two of them growing) near $y=0$ where the dispersion function approaches $D(y)=1$. The complex solutions near $y=0$ are of physical interest, because they describe growing or damped waves in the plasma.

The method of analytically approximating the roots of interest is as follows: The dispersion function of Eq. (6) may be rearranged into a hexic dispersion equation relating x and y as follows,

$$y^6-y^4(1+2x^2+\epsilon)+y^2(x^2-1+2\epsilon)x^2-\epsilon x^4=0\,. \tag{7}$$

If we neglect the small parameter ϵ in the coefficients of y^4 and y^2, the dispersion relation can be approximated as

$$y^6-y^4(1+2x^2)+y^2(x^2-1)x^2-\epsilon x^4=0\,. \tag{8}$$

Since Fig. 5 has shown y to be a small number for the roots of interest. We neglect the terms multiplied by y^6 and y^4 in Eq. (8), and obtain

$$y^2\approx \epsilon x^2/(x^2-1)\,. \tag{9}$$

A resonance with growing and damped waves occurs in the vicinity of

$$x^2\approx 1\,, \tag{10a}$$

$$\omega_{pe}^2\approx k^2v^2\,; \tag{10b}$$

thus, the gain becomes infinite in the neighborhood of $x\approx\pm 1$.

Actually, y^2 cannot go to infinity, because the next higher power of y cannot now be neglected. Retaining the y^4 term in Eq. (8), one obtains

$$y^4(1+2x^2)-y^2(x^2-1)x^2+\epsilon x^2\approx 0\,. \tag{11}$$

In the vicinity of $x^2\approx 1$,

$$3y^4\approx -\epsilon\,. \tag{12}$$

The complex roots of this equation are

$$\omega=\pm\frac{(\omega_{pe}\omega_{pi})^{1/2}}{2^{1/2}3^{1/4}}\pm i\,\frac{(\omega_{pe}\omega_{pi})^{1/2}}{2^{1/2}3^{1/4}}\,. \tag{13}$$

There are four roots for the frequency, one root pair with growth and with damping propagating to the right, a second root pair with growth and with damping, to the left. The frequency and growth rate are numerically equal in this instance, and are given by

$$\omega_{gm}=\frac{(\omega_{pe}\omega_{pi})^{1/2}}{2^{1/2}3^{1/4}}=0.537\omega_{pe}\left(\frac{m}{M}\right)^{1/4}. \tag{14}$$

Going to the next higher power of y in Eq. (8) (6th, and last), we only obtain a correction of a few percent to Eqs. (13), (14), and (20).

If the treatment given here is extended to three dimensions, a weak cosine dependence is found [multiply the expression of Eq. (13) for ω by $|\cos^{1/2}\theta|$]. However, the gain still peaks for $\theta=0$, so the one-dimensional treatment still yields the correct observable result.

The full dispersion equation given by Eq. (7) has been solved on a computer by a procedure which obtains all of the real, imaginary, or complex solutions to the equation. The complete dispersion curves are shown in Fig. 6 for deuterium ions. In this figure, only solutions with positive frequencies (or growrh rate) are shown as solid terms (dotted lines). Above a dimensionless wave number of $x\gtrsim 1.0$, all six solutions to the dispersion relation are real. Four of these solutions are asymptotically equal to waves with $\omega=kv$, which propagate with the electron beam velocity v. The remaining two of these real solutions are asymptotic to the ion plasma frequency for deuterium, ω_{pi}, shown by the arrow on the left-hand side. Below a dimensionless wavenumber of $x\approx 1$, there are four purely imaginary solutions and two real solutions. The two real solutions are asymptotic to the electron plasma frequency, ω_{pe}, as $x\to 0$. The four solutions which have waves with purely imaginary ω are growing or decaying but are not observable because they do not radiate. The two solutions with a purely real frequency ω are observable, but are not growing.

It is not evident from Fig. 6, but there is a very narrow window in the immediate vicinity of $x=1$, for which complex solutions to Eq. (7) exist. This narrow window for deuterium gas is plotted in Fig. 7(a) with a greatly expanded abscissa. The lobes to the right and left represent the purely real and purely imaginary solutions to the equations which are evident in Fig. 6. In the narrow window from $0.972\leqslant x\leqslant 1.028$,

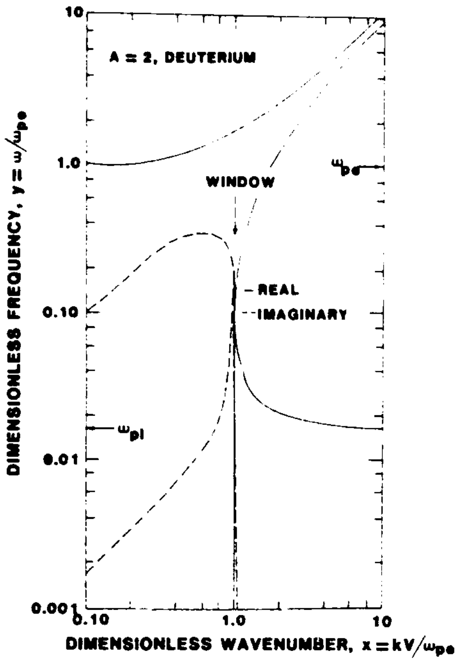

FIG. 6. The dispersion relation for the two interpenetrating electron beam case, with deuterium background ions. Only positive growth rates (dotted lines) and positive real frequencies (solid lines) are shown. A very narrow window exists around $X=1$ for which real and imaginary solutions co-exist.

the dispersion relation has complex solutions with positive real and imaginary parts coexisting, so that such waves should be observable and growing. The four complex solutions in this window comprise waves propagating to the right and to the left, each of which has one component which is growing and one component which is damped. The perturbation analysis has isolated the peak value of the product of real and imaginary parts of ω given by Eqs. (13) and (14). This perturbation result is shown in Fig. 7(a), and occurs where the real and imaginary parts of the complex solutions intersect at $x=1.0$.

The window in which complex solutions exist is an extremely narrow one. The wavenumbers, and, hence, wavelength of the radiation resulting from these growing waves, should occur within a very narrow bandwidth. This window becomes narrower, the larger the atomic mass number of the ions participating in the interaction. In Fig. 7(b) is shown the radiating window for xenon ions as the background gas. In this case, the total window width is less than 1% of the wavelength.

One can determine the width of the window boundary by a perturbation procedure very similar to that used here. In the window, it is evident from Figs. 6 and 7 that $y \ll 1$; so, if we neglect y^6 in Eq. (8), where the small parameter ϵ has already been dropped from the coefficients of the y^2 and y^4 terms, one obtains

$$y^4(1+2x^2) - y^2(x^2-1)x^2 + \epsilon x^4 \approx 0 . \quad (15)$$

This approximation for the dispersion curves in the region of the window can be solved as a biquadratic, to obtain

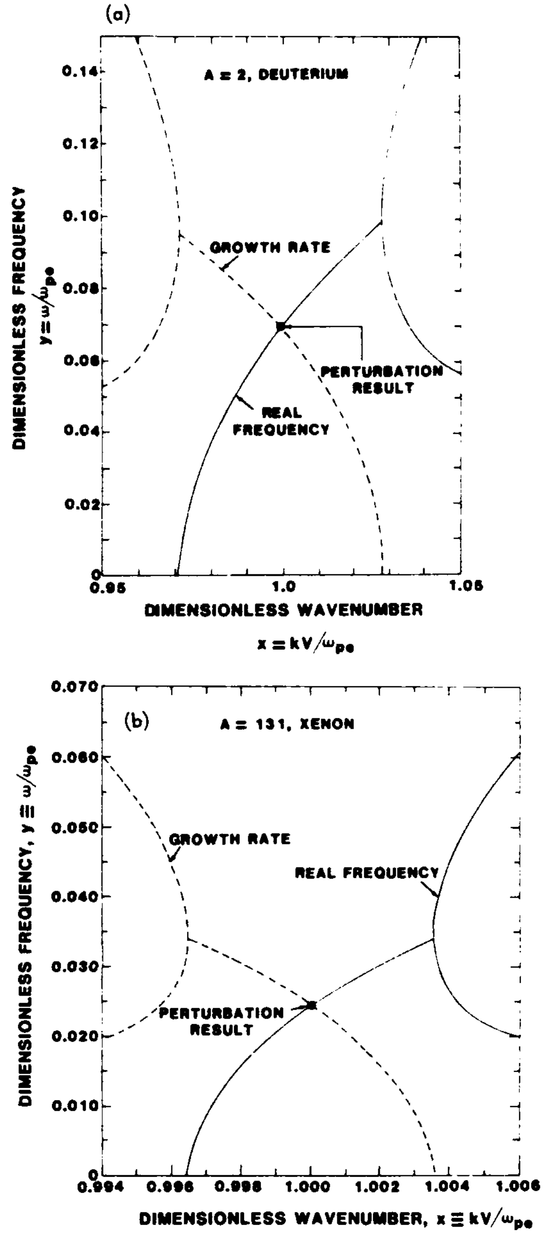

FIG. 7. The narrow window around $X=1$ for which positive real and imaginary roots co-exist. (a) The window for deuterium gas, $A=2$, and (b) for xenon gas, $A=131$.

$$y^2 \approx \frac{x^2\{(x^2-1) \pm [(x^2-1)^2 - 4\epsilon(1+2x^2)]^{1/2}\}}{2(1+2x^2)} . \quad (16)$$

The boundary of the window occurs when the solutions change from purely real or purely imaginary to complex. This transition occurs when the discriminant of Eq. (16) is 0. This condition requires that

$$(x^2-1)^2 - 4\epsilon(1+2x^2) \approx 0 . \quad (17)$$

If the dimensionless wavenumber x is expanded about the window with width δ, we find x to be

$$x = \pm 1 \pm \delta . \quad (18)$$

From Fig. 7, which shows the windows for deuterium and xenon, it is evident that $\epsilon \ll \delta$. If we substitute Eq. (18) into Eq. (17), and neglect higher powers of ϵ, δ,

and their products, we obtain the following expression for the window half-width

$$\delta^2 = 3\epsilon , \tag{19}$$

or this can be expressed

$$\delta = \pm\left(\frac{3m'}{M}\right)^{1/2} = \pm \frac{0.0404}{A^{1/2}} . \tag{20}$$

Thus, the window width for this emission is inversely proportional to the square root of the atomic mass number of the ions in the plasma. This approximation yields $\delta = 0.0286$ for $A = 2$ (deuterium), and $\delta = 0.00353$ for $A = 131$ (xenon), which are in excellent agreement with the exact numerical solutions presented in Figs. 7(a) and 7(b).

C. Comparison with experiment

The agreement of the geometric mean frequency, given by the growing solution of Eq. (13) with the experimental observations is indicated by the straight lines on Figs. 3(a) and (b). The lower line is the relation predicted by Eq. (14) for the chord-averaged electron number density from a microwave interferometer, which is plotted on the abscissa; the upper straight line is predicted by Eq. (14) for the maximum number density on the plasma axis, assuming a parabolic radial density distribution. The points outside these lines at low number density are the result of a systematic error occasioned by measuring these low densities. The agreement between theory and experiment is very good. Over a factor of more than two in magnetic field, and more than forty in density, the predicted frequency has both the proper functional and quantitative dependence.

The theoretical expression with which we are comparing these data is appropriate to an infinite plasma. One must consider finite size effects if the parameter ka is not large compared with unity, where k is the wave wave number of the radiation. A characteristic minor radius of this plasma is $a = 0.06$ m, and a characteristic beam energy (equal to the electrostatic potential well depth along the magnetic field lines) is about 1.0 keV, yielding a beam velocity of $v_b = 1.9\times10^7$ m/sec. For these conditions, the finite size parameter ka for the densities observed in this experiment (see Fig. 3) ranges over $11 \leq ka \leq 80$, so the inifinite plasma assumption is valid.

Equation (14) predicts a dependence on the one-fourth root of the ion mass which was not confirmed in these experiments, which were restricted to deuterium gas. While it is encouraging that substitution of the deuterium mass into Eq. (14) yields such good agreement with the measurements, further work is desirable to check this dependence. Such experiments are now in progress, and preliminary results are consistent with the predicted mass dependence.

D. Finite temperature effects

One important correction to the calculation presented here is the effect of finite particle temperatures. In the present experiment the ions were much hotter than the electrons (500 eV kinetic temperature relative to 30 eV), the electron beam energies are estimated to be about 1 keV, the ion thermal velocity was less than the electron beam velocity by about a factor of 76, and the ion thermal velocity was about one fifth the phase velocity of the wave for such conditions; the ion Landau damping as well as ion thermal pressure modifications to the dispersion relation need to be examined.

Our analysis, to be described in detail, shows that the growing and emitting frequencies in the wavelength window around $kv_e \approx \omega_{pe}$ are remarkably invariant to changes in ion temperature. Only when the ion thermal velocity becomes equal to the elecron beam velocity do the growing, emitting solutions become very small in magnitude. An interesting feature of the analysis is that the finite ion temperature seems to eliminate the damped solutions, but not the growing solutions. Thus, ion Landau damping accentuates growth, in the tradition of the resistive-wall traveling-wave amplifier tube.

The basic modification to the original, zero-temperature dispersion relation. Eq. (1), is done as follows. The ion temperature component is introduced as a group of ion beams.[21]

$$\frac{\frac{1}{2}\omega_{pe}^2}{(\omega - kv)^2} + \frac{\frac{1}{2}\omega_{pe}^2}{(\omega + kv)^2} + \frac{\sum_j \omega_{pij}}{(\omega - kv_{ij})^2} = 1 . \tag{21}$$

Here, ω_{pij} is the ion plasma frequency of the jth beam, and v_{ij} is the velocity of the jth ion beam.

Next, the density of each ion beam n_{ij} is derived from the total ion density by means of an ion velocity distribution function $f(v_{ij})$, as

$$n_{ij} = n_0 f(v_{ij})\Delta v_{ij} , \tag{22}$$

where, Δv_{ij} is the spacing in velocity space between the many beams. The dispersion relation for the ion term can be written as will be shown, where ω_{pi} is the ion plasma frequency due to the total on density

$$\omega_{pi}^2 \sum_j \frac{f(v_{ij})\Delta v_{ij}}{(\omega - kv_{ij})^2} . \tag{23}$$

Letting $\Delta v_{ij} \to 0$ allows this term to be expressed in integral form. Our dispersion relation now appears as

$$\frac{\frac{1}{2}\omega_{pe}^2}{(\omega - kv)^2} + \frac{\frac{1}{2}\omega_{pe}^2}{(\omega + kv)^2} + \omega_{pi}^2 \int_{-\infty}^{\infty} \frac{f(v_i)dv_i}{(\omega - kv_i)^2} = 1 . \tag{24}$$

It is important to remember that v in the electron terms is the electron beam velocity, while v_i is the ion thermal velocity.

The value for $f(v_i)$ is given by the one-dimensional Maxwellian distribution

$$f(v_i) = \frac{1}{\sqrt{\pi}}\left(\frac{m}{2kT_i}\right)^{1/2} \exp -\left(\frac{mv_i^2}{2kT_i}\right) . \tag{25}$$

Let us define $v_0 = (2kT_i/m)^{1/2}$, so that $f(v)$ can be written as

$$f(v_i) = \frac{1}{\sqrt{\pi}}\frac{1}{v_0} \exp -\left(\frac{v_i^2}{v_0^2}\right) . \tag{26}$$

Next, let $v_i = v_0 z$, where z is a dimensionless para-

meter; then,

$$f(v_i)=\frac{1}{\sqrt{\pi}}\,\frac{1}{v_0}\exp(-z^2)\,. \tag{27}$$

If this is put into our dispersion relation, we obtain,

$$\frac{\frac{1}{2}\omega_{pe}^2}{(\omega-kv)^2}+\frac{\frac{1}{2}\omega_{pe}^2}{(\omega+kv)^2}+\frac{\omega_{pi}^2}{k^2v_0^2}\,\frac{1}{\sqrt{\pi}}\int_{-\infty}^{\infty}\frac{\exp(-z^2)}{(\xi-z)^2}\,dz=1\,, \tag{28}$$

where $\xi=\omega/kv_0$. In this formalism, the integral is seen to be the derivative of the plasma dispersion function, and is tabulated in the literature.[22] For computational purposes, we again use the reduced form, where $y=\omega/\omega_{pe}$, $x=kv/\omega_{pe}$, and $\epsilon=\omega_{pi}^2/\omega_{pe}^2=m/M$. Our dispersion relation becomes

$$\frac{\frac{1}{2}}{(y-x)^2}+\frac{\frac{1}{2}}{(y+x)^2}+\frac{\epsilon}{x^2}\,\frac{1}{(v_0/v)^2}\,\frac{d}{d\xi}Z(\xi)=1\,. \tag{29}$$

If we let the ratio $(v_0/v)^{-1}=\beta$, our equation appears in final form as

$$\frac{\frac{1}{2}}{(y-x)^2}+\frac{\frac{1}{2}}{(y+x)^2}+\frac{\epsilon}{x^2}\,\beta^2\,\frac{d}{d\xi}Z(\xi)=1\,. \tag{30}$$

For actual computational purposes, Eq. (7) is used, except that ϵ is replaced by ϵ', where

$$\epsilon'\equiv\frac{\epsilon}{A}\,\frac{y^2\beta^2}{x^2}\,\frac{d}{d(\beta y/x)}\,Z\left(\frac{\beta y}{x}\right). \tag{31}$$

Here, ϵ is the electron-proton mass ratio, A is the atomic mass number of the gas, and ξ is replaced by $\beta y/x$, so that y and x appear in the plasma dispersion function.

E. Numerical computations

All computations were performed at the Univesity of Tennessee Computer Center. An IBM 370/3031 and a DEC KL-10 were used. For the zero temperature case, the polynomial of Eq. (7) was represented as a square matrix which has eigenvalues at the roots of the polynomial. The eigenvector-eigenvalue analysis package EISPACK[23,24] was used to find the solution. The method used for the finite-temperature case was an extension of that described herein. The Fried–Conte function was approximated using a Taylor's series in a disk centered at the origin of the complex plane; an asymptotic expansion was used outside the disk. An interactive procedure was used to obtain the solution of Eq. (30) by approximating with a polynomial with cofficients evaluated at the current estimate of the root. This procedure was repeated for each root. This method allowed the resolution of roots which were close neighbors; specifically, the points at which the roots became complex, as a function of x, could be determined accurately.

A cross check on ths process of evaluating the equations was done by computing the differential, as a function of ion kinetic temperature T_i,

$$y_2=y_1+\Delta y=y_1+\frac{dy}{d\epsilon}\,\frac{d\epsilon}{dT_i}\,\Delta T_i\,. \tag{32}$$

In this fashion, one could take a particular solution, generally the $T_i=0$ zero-temperature solution, and move from one set of y, x curves to another. We find that no serious changes occur for growing solutions, but that damped solutions often become unphysical, oscillate wildly, for small values of the ion temperature.

One result seems to be very significant. The damping for waves moving slowly in the "window" (the region where growing and propagating waves exist) is much greater than the growth for waves of the same velocity.

Thus, absorption by the damped waves should prevent slow-moving growing waves from radiating. This may help explain why only waves near the maximum predicted radiating frequency are actually observed.

Typical computational results for finite ion temperatures are shown in Fig. 8 for the window near $x=1$ for deuterium. The curve for $\beta=\infty$ corresponds to an ion thermal velocity of zero and has been presented previously.

The value of $\beta=15$ corresponds to an electron beam velocity to ion thermal velocity ratio of 15. This number was chosen because the wave velocity corresponding to data points in the middle of this figure (y/x) is also about 15 times less than the electron beam velocity i.e., for β of 15, the wave velocity is comparable to the ion thermal velocity. The remarkable result is that most of the main features of the instability—"window," growing mode, frequency of emission—do not change a great deal. The lower velocity real ion mode, and the more slowly growing, nonpropagating mode both do not appear. Our perturbation analysis suggests that ion

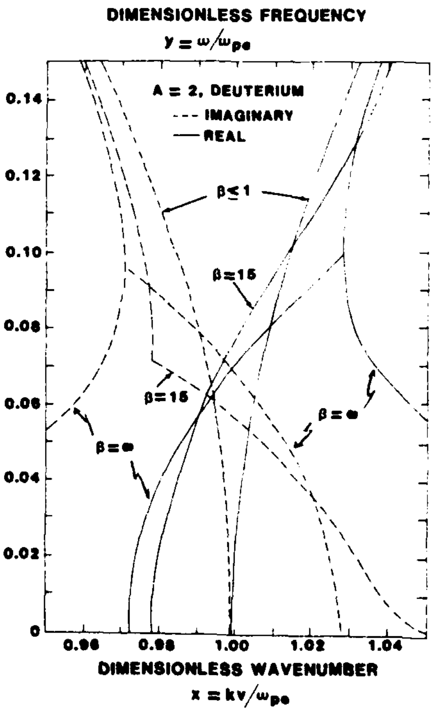

FIG. 8. Real and imaginary solutions (positive branches only) in the vicinity of $x=1.0$ for deuterium, and values of the ion temperature parameter β of 1.0, 15, and ∞. The latter is equivalent to the zero ion kinetic temperature case.

Landau damping converts both modes to nonpropagating damped modes, but our study of these "missing modes" is as yet incomplete.

The value of $\beta = 1$ corresponds to electron beam velocity equal to ion thermal velocity. At this ion temperature, the "window" closes, and no emitting (growing and propagating) modes appear to exist. A very similar curve is obtained if the ion-electron mass ratio, ϵ is set equal to zero (infinitely heavy ions) in Eq. (20). The basic feature in both cases is that the ions cease to participate in the instability, which then becomes a two-electron-beam instability.

In general, the studies of finite ion temperature effects show no drastically changed microwave emission until the ion thermal velocity greatly exceeds the plasma wave velocity.

F. Effective plasma conductivity

We can estimate the effective plasma conductivity resulting from electron beam-beam interactions in the following fashion.[14,20] A particular mode grows exponentially, then saturates. Just before it saturates, it absorbs a great deal of energy ΔE. During this time period Δt during which the absorption takes place, the power absorbed is given by $\Delta E/\Delta t$. After this mode saturates, it is replaced by another mode and the process continues.

The reason the instability is so effective in heating the plasma is that the resistive part is primarily an electron-electron instability. If we immobilize the ions by setting $\epsilon = 0$ (infinitely heavy ions), the equations become more simple, and can be solved analytically. The calculations for the effective resistivity in the case of infinite ion mass proceeds as follows; setting $\epsilon = 0$ produces the infinite ion mass. The dispersion relation is reduced as

$$y^6 - y^4(1 + 2x^2) + y^2(x^2 - 1)x^2 = 0 . \tag{33}$$

The term y^2 may be factored out: this term is arbitrary. It corresponds to being able to have arbitrary ion modes propagating in the $\pm x$ direction without interacting (because of ∞ mass) with the electrons. The resulting quartic may be solved as

$$y^2 = \tfrac{1}{2}[1 + 2x^2 - (1 + 8x^2)^{1/2}] . \tag{34}$$

For the negative solution of Eq. (34) at $x = 1$, then $y = 0$. The latter corresponds to the location of our "window" in this degenerate case. The positive solution concerns a nongrowing wave of no interest for this computation.

We find the maximum growth by differentiating Eq. (34) and setting the derivative equal to zero. We obtain two zeros, one at $x = 0$, which corresponds to the uninteresting case of $y = 0$, and the second giving our maximum growth rate at

$$x = \pm\tfrac{1}{2}(\tfrac{3}{2})^{1/2} = \pm 0.612 . \tag{35}$$

This corresponds closely to the graphical result, for ϵ corresponding to deuterium, of 0.60.

Placing this value of x in our equation for y, we obtain for the maximum growth

$$y = 0.353i . \tag{36}$$

Using *half* this value in our relationship for y vs x, we find the new value of x to be 0.190. Thus, to reduce the gain to half its value, the electron beams must slow from $x = 0.612$ to $x = 0.190$, the velocity must drop to one third of its original value, and the beam energy drop to one ninth its initial value. Thus, the instability does not saturate until essentially all its beam energy is extracted.

The energy change ΔE is

$$\Delta E = \tfrac{1}{2}mnv^2 . \tag{37}$$

The time in which this occurs, Δt, is

$$\Delta t \approx 1/0.353\omega_{pe} . \tag{38}$$

The effective power loss from the two beams W is

$$W = \frac{1}{\sigma_{bb}}\left[\left(\frac{nev}{2}\right)^2 + \left(\frac{nev}{2}\right)^2\right] = \frac{\Delta E}{\Delta t} . \tag{39}$$

Solving Eqs. (37) to (39), we find the effective conductivity σ to be

$$\sigma_{bb} = 2.83\epsilon_0\omega_{pe} . \tag{40}$$

Where we have designated the conductivity σ_{bb} for the electron beam-beam interaction

$$\sigma_{bb} = \frac{\epsilon_0\omega_{pe}}{0.35} = 2.86\epsilon_0\omega_{pe} . \tag{41}$$

We can compare Eq. (41) with the estimate of the Buneman conductivity from Hirose,[14]

$$\sigma_B \cong 2\epsilon_0\omega_{pe}(M/m_e)^{2/3} . \tag{42}$$

Our value of the conductivity is reduced by the 2/3 root of the electron-ion mass ratio as compared with the Buneman value, or for deuterium, by a factor of 0.0060. This instability thermalizes about 166 times faster and is therefore extremely effective in heating plasma.

As pointed out previously, the very high rate of dissipation calculated in Eq. (39) will not eliminate the beam-beam nature of the electron distribution function. Electrons will be constantly produced by ionization, fall down the axial electrostatic potential well to the midplane, and replenish the distribution. Since electrons eventually lose parallel velocity, they will be transported radially across field lines and ultimately lost on the positive midplane electrode ring.

IV. DISCUSSION

A. Comparison with other beam-plasma interaction mechanisms

The experimental relation between emission frequency and electron number density in Fig. 3 is not qualitatively consistent with any of the classical beam-plasma interactions which give to emission near the electron plasma frequency.[7-10] The only known plasma frequency that is even approximately consistent with the data of Fig. 3 is that first described by Buneman[6] We considered the possibility that the emission might

be due to the Buneman instability, which occurs at a frequency given by[3,4,6]

$$\omega_B = \frac{\omega_{pe}^{1/3}\omega_{pi}^{2/3}}{2^{4/3}} = 0.397\,\omega_{pe}\left(\frac{m}{M}\right)^{1/3}. \tag{43}$$

The ratio of the geometric mean emission frequency given by Eq. (14) to the Buneman frequency is given by

$$\frac{\omega_{gm}}{\omega_B} = \frac{2^{4/3}}{2^{1/2}3^{1/4}}\left(\frac{M}{m}\right)^{1/12} = 2.533A^{1/12}. \tag{44}$$

For deuterium gas with $A=2$, which was used in the experiments described here, the ratio of the geometric mean to the Buneman frequency is a factor of 2.7. Since the frequency is proportional to the square root of the electron number density, there is no realistic possibility that the average electron number density in the plasma could be the required factor of 7.2 times larger than the average measured by the microwave interferometer which would be required to give a Buneman frequency in agreement with our measurements. In addition, the Buneman instability requires a large toroidal current, which does not exist in this plasma.

Equation (42) demonstrates that the parallel plasma resistivity to be expected from the two interpenetrating beam mechanisms is from several hundred to several thousand times that which can be expected from the single beam-plasma interaction of Buneman, which heretofore has been the highest known plasma resistivity. In retrospect, it is perhaps not surprising that the general level of turbulence, and of energy dissipation in the interpenetrating beams, is much higher than that of a single beam interacting with the plasma. The two interpenetrating beams will interact with themselves as well as the background ion population, and these additional interactions will increase the general level of energy dissipation and the effective resistivity of the plasma.

The relative magnitude of various dissipative mechanisms can be illustrated by a plasma (or conductor) one square centimeter in cross section and one meter long. This (fusion-related) plasma chosen as an example is a deuterium plasma with $A=2$, $Z=1$, $n_e = 10^{14}$ ions per cubic centimeter, and an electron kinetic temperature $T_e = 10$ keV. The interpenetrating electron beam instability described by the conductivity of Eq. (41) would yield a resistance of 700 Ω over a 1 m long column of such a plasma. The "turbulent" conductivity from the single beam plasma interaction mechanism of Buneman, Eq. (42) would yield a resistance of 4.21 Ω; the classical Spitzer conductivity due to the binary collisions of the electrons in such a plasma would be about 10 μΩ, and the resistance of a copper bar of the same dimensions would be about 167 μΩ,

A potential application of the geometric mean plasma emission of particular significance to electromagnetic communications is excitation of electromagnetic radiation by this mechanism in the magnetosphere. This emission mechanism is excited at frequencies given by

$$\nu_{gm} = \frac{737 n_e^{1/2}}{A^{1/4}}\ \text{Hz}, \tag{45}$$

where n_e is in electrons per cubic centimeter, and A is the atomic weight of the background ions. A characteristic maximum number density in the ionosphere is about $n_e = 1.5\times10^7$ per cubic centimeter at an altitude of 370 km, where atomic oxygen ions are dominant. The geometric mean frequency corresponding to these conditions is 1.4 MHz. If emissions were to result from mirroring or counter-streaming electrons below this altitude, all frequencies below this value could be excited, and the resulting rf radiation trapped in the cavity between the ionosphere and the earth.

The configuration which is most likely to contain two interpenetrating electron beams interacting with a background ion population is the Penning discharge, where electrons are trapped on magnetic field lines for durations much longer than their collision time or their transit time along the discharge. It may be no accident that Penning discharges characteristically have radial and axial electric fields[25-27] which are stronger than can be accounted for by conductivities based on binary collisions, or even single beam-plasma interactions of the Buneman type. Axial and radial electric fields on the order of 1 kV/cm have been observed in some cases.[25-27]

V. CONCLUSIONS

We have experimentally observed and derived theoretically a previously unrecognized mechanism for generating electromagnetic emissions and anomalous resistivity from the interaction of equal and oppositely directed electron beams with a background of heavy ions. This interpenetrating electron beam interaction can produce electromagnetic emissions in the vicinity of the geometric mean plasma frequency, the radiation from which is restricted to a very narrow window in wavelength. The width of this emission window is inversely proportional to the square root of the ion mass. The rate at which energy is dissipated by the electron beams in the plasma is predicted to be at least a hundred times that of the Buneman instability. This increased rate of dissipation, or higher resistivity, can be understood on the basis that the equal and oppositely directed electron beams are interacting with themselves, as well as with the background ion population. This high effective resistivity may explain the very high radial and longitudinal electric fields which have been observed in Penning discharges, a configuration which promotes the two interpenetration beam interaction.

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A PAIRED COMPARISON OF HIGH FREQUENCY RF EMISSION FROM TWO CONFIGURATIONS OF ELECTRIC FIELD DOMINATED PLASMA

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Abstract: We report paired comparison observations of RF emission from two steady-state electric field dominated plasmas, a classical Penning discharge operating in an axially uniform magnetic field, and a modified Penning discharge operating in an axisymmetric magnetic mirror. Measurements were made at frequencies up to 70 GHz. Much RF activity was observed below 1.0 GHz.

1. Introduction

Radio Frequency (RF) emissions from plasmas can yield diagnostic information about the electron number density (from emissions at the electron plasma frequency), and the ionic species (from emissions at the ion plasma frequency); about turbulence and nonlinear mode coupling in the plasma; and about physical processes in the plasma such as rotating spokes arising from the E/B driven diocotron instability and/or low frequency MHD instabilities. Such near-field emission phenomena are best observed in steady-state electric field dominated plasmas where conventional RF spectral analysis equipment has enough time to operate (as opposed to pulsed experiments lasting less than one second), and which have a substantial energy input through axial and transverse electric fields which penetrate the plasma. Such plasmas are generated by the classical (ref. 1) and modified (ref. 2) Penning discharges. These are known to be penetrated by strong radial and axial electric fields, up to kilovolts per centimeter, to operate with high levels of electrostatic turbulence, to heat ions by an E/B drift mechanism, and to emit RF radiation in the near field over a wide range of frequencies (refs. 3-6). In this paper we report a paired comparison of RF emissions from a classical Penning discharge, (with the plasma in a uniform magnetic field), with emissions from a modified Penning discharge which is operated in a magnetic mirror.

2. The Modified Penning Discharge

The modified Penning discharge (ref. 2) is operated in a 5:1 magnetic mirror ratio configuration which is intended to simulate the high mirror ratios of magnetospheric plasmas. The plasma is approximately 10 cm in diameter at the midplane, one meter in length, and has a maximum magnetic field up to 0.4 Tesla at the mirror throat. A schematic of the modified Penning discharge is shown in Figure 1. The plasma was operated with helium and argon gas, and is

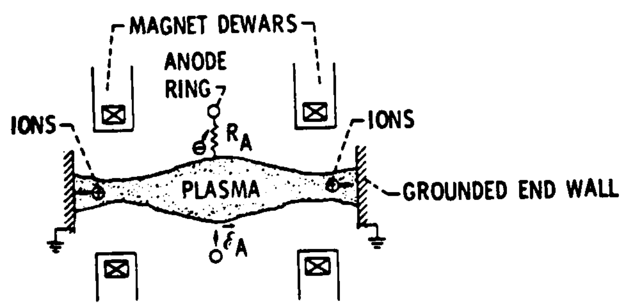

Figure 1. Schematic of the modified Penning discharge.

enclosed in a glass vacuum system which allows RF radiation to escape.

This modified Penning discharge produced two modes of RF emission, as shown in Figure 2. The low pressure mode (Mode I) shown on Fig. 2A is apparently a manifestation of the geometric mean emission frequency (Ref. 5) and harmonics out to about 500 MHz. The high pressure mode (Mode II) on Fig. 2B appears to be a manifestation of diocotron-like spokes rotating with the E/B drift velocity, with as many as 30 harmonics, sometimes visible to 500 MHz.

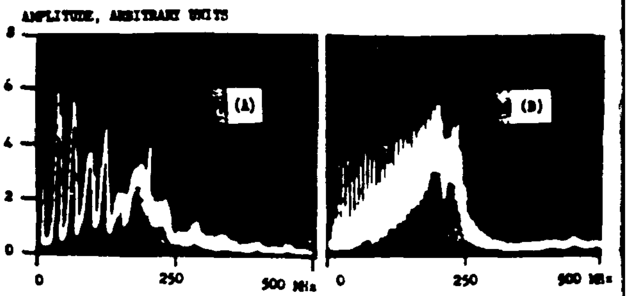

Figure 2. Spectrum of near-field emissions from the modified Penning discharge operating with helium gas at a 5:1 mirror ratio with $B_{max} = 0.39$ Tesla. A) Mode I operation at $p_0 = 4.4 \times 10^{-5}$ Torr, electrode voltage $V_a = 4.0$ kV, and electrode current $I_a = 3.0$ mA. B) Mode II operation at $p_0 = 2.3 \times 10^{-4}$ Torr, $n_e = 7.6 \times 10^9/cm^3$, $V_a = 2.0$ kV, and $I_a = 46$ mA.

3. The Classical Penning Discharge

The classical Penning discharge (ref. 1) was operated with a uniform magnetic field up to 0.43 Tesla, and produced a plasma about 10 cm in diameter and one meter long. The plasma was operated in the steady state with helium and argon gas, and a glass vacuum system allowed RF radiation to escape. A preliminary spectrum of RF emission from 0 to 500 MHz is shown on Fig. 3. This plasma appears to operate in only a single mode, and to produce spectra of which Figure 3 is characteristic for both helium and argon gas. The example shown has 27 harmonics extending out to 500 MHz, and harmonics have been observed to 1.0 GHz. Many nonlinear mode coupling phenomena are apparent, including an example of plasma "lability" in which the spectral amplitude is greatest around the 8th harmonic at 200 MHz. The fundamental appears to be an example of the geometric mean emission frequency (ref. 5). RF detection equipment was used at frequencies of 10, 35, and 70 GHz, and no emissions were observed under the existing conditions.

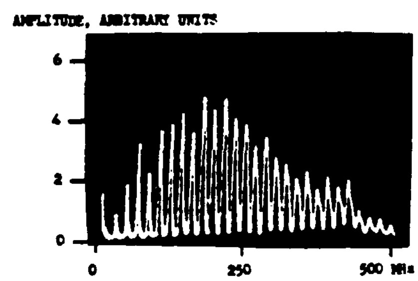

Figure 3. Spectrum of near field emissions from the classical Penning discharge with uniform magnetic field of B = 0.285 Tesla, $p_0 = 2.3 \times 10^{-4}$ Torr of argon gas, electrode voltage $V_a = 2.1$ kV, and electrode current $I_a = 31$ mA.

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ION HEATING AND CONTAINMENT IN AN ELECTRIC FIELD BUMPY TORUS (EFBT) PLASMA

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In the Electric Field Bumpy Torus (EFBT), gross confinement is provided by a bumpy torus magnetic field, and plasma heating, macroscopic stabilization, and enhanced confinement by externally applied electric fields. In this magneto-electrically confined plasma, the radial electric field has exceeded 1 kV/cm at the plasma boundary and has penetrated inward to at least one-half the plasma radius.

These high dc radial electric fields lead to strong low frequency fluctuations of the density and potential, and radially inward fluctuation-induced transport against the radial plasma density gradient. With negative electrode polarity, the particle confinement was a balance of two processes: radial infusion of ions in sectors of the plasma not containing electrodes, resulting from fluctuation-induced transport in the radially inward dc electric fields; and ion losses to the electrodes, each of which acted like a Langmuir probe in ion saturation to extract ions from the plasma. A simple model predicts that the particle containment time is proportional to the plasma volume, and this was experimentally observed. The ions and electrons receive energy from external power supplies through the imposed radial electric field, and the E/B drift velocities thermalize to kinetic temperatures which can reach several kilovolts. In the steady-state NASA-Lewis EFBT experiment, the enhancement of confinement provided by negative plasma bias made possible simultaneously an average number density $n_e = 3.2 \times 10^{12}/\text{cm}^3$, an ion kinetic temperature of 300–500 eV, and a particle containment time of $\tau = 2.5$ ms in an 82 liter plasma.

1. Introduction

Only the electric, magnetic, and gravitational fields of fo :e are available for the steady state confinement of fusion plasmas. Gravitational fields are, of course, not available on a human scale. It has been shown by Post [1] that pure electrostatic confinement of fusion-grade plasmas would require impracticably high electric field strengths, and moreover would violate Earnshaw's theorem [1,2]. Earnshaw's theorem [2] states that a collection of positive and negative charges cannot be stably confined by any purely electrostatic potential distribution. Pure magnetic confinement, in which a plasma is confined solely by strong steady-state magnetic fields, has been the dominant approach to plasma confinement since the beginning of controlled fusion research.

This paper will attempt to demonstrate that the mainline approaches to magnetic fusion have overlooked an attractive possibility for plasma confinement–magnetoelectric confinement, by which is meant the simultaneous use of externally applied electric and magnetic fields. In this approach, gross confinement of the plasma is provided by a background magnetic field. Electric fields are imposed on the plasma by external power supplies in such a way that the plasma becomes electric field dominated (that is, electric fields far stronger than ambipolar values penetrate the plasma over a significant fraction of its dimensions). In this paper, we will show that such electric fields can be created, and that they can have a beneficial effect on the confinement, transport, heating, and stability of the plasma.

1.1. Previous research on magnetoelectric confinement

The principle of enhancing magnetic confinement by imposing strong, dc electric fields perpendicular to the confining magnetic field was demonstrated in an open-ended magnetic geometry by George in 1961 [3]. Several investigators have since applied strong electric fields to plasmas in cusp [4–6] or mirror [7,8] configurations in an effort to enhance the otherwise poor confinement properties of these open-ended geometries. In other experiments, strong radial electric fields have been applied to plasmas in mirror geometries for the primary purpose of heating ions to high energies [9,10], or to simulate magnetospheric plasmas [11,12].

Externally applied electric fields have not thus

far played a role in toroidal plasma confinement. Theoretical papers by Kovrizhnykh [13,14] present the implications of ambipolar electric fields for diffusional transport of toroidal plasmas. Stix [15,16] examined theoretically how a radial electric field, arising from preferential loss on divertors or limiters of large gyroradius ions, would affect the confinement and stability of a toroidal plasma. Stix [15,16] also coined the term "Magnetoelectric Confinement". The ambipolar electric fields considered by Kovrizhnykh and Stix were relatively weak and resulted in an E/B drift velocity much less than the particle thermal velocity. Moreover, these ambipolar electric fields were not directly imposed by external power supplies. They therefore could neither do work on the plasma to heat it nor assist in its confinement by dynamic stabilization.

It was suggested in 1967 [17] that a toroidal plasma could be heated and confined in an *E*lectric *F*ield *B*umpy *T*orus (EFBT) configuration, in which gross confinement is provided by a bumpy torus magnetic field configuration. It was further proposed that the plasma be operated in a toroidal electrostatic potential well, created by biasing the plasma in such a way that it would operate as a toroidally linked system of modified Penning discharges.

The bumpy torus configuration receives its name from the shape assumed by the confined plasma and consists of a number of coils (12 for the NASA-Lewis facility described herein) arranged in a toroidal array. This magnetic geometry was proposed by Gibson et al. [18], who later extensively investigated single-particle motion relevant to it [19]. Geller [20] operated a pulsed plasma source in a bumpy-torus geometry and reported near-classical confinement of the afterglow plasma [21]. Fanchenko et al. [22] have investigated turbulent heating in a bumpy torus plasma; and Dandl et al. [23] have carried out extensive experimental investigations on electron cyclotron resonance heating in the Oak Ridge ELMO bumpy torus device. The ELMO creates a stable magnetic well in each sector of the torus with high-beta, hot electrons that are generated by absorption of radiofrequency (rf) power; the ion population is heated by binary collisions with the more energetic electrons.

Recent experiments on the Macrotor tokamak by Taylor et al. [24–26] have served to corroborate the results summarized in this paper. They find that electrostatic confinement of a tokamak plasma, achieved with a biased limiter, yielded a significant improvement in the confinement of the tokamak plasma [26] and that negative bias (which produced an electrostatic potential well for ions) significantly improved ion heating as well as confinement [24, 25].

The NASA Lewis EFBT project was preceded by an investigation of the modified Penning discharge in a simple magnetic mirror configuration. During these investigations, the presence of kilovolt Maxwellian ions, isotropic in velocity space, was established [27–31]. The plasma in the modified Penning discharge was found to be highly turbulent [32], and this turbulence evidently plays a role in the thermalization of the ion energies which result from E/B drift in the crossed electric and magnetic fields [29].

Previous investigations of the EFBT plasma, at relatively low densities and confinement times [33,34], have shown that – in common with Penning discharges and magnetron devices – the plasma formed rotating spokes that gyrated around its minor circumference at nearly the E/B drift velocity. As was the case in the simple, modified Penning discharge [27–31], the ions in the rotating spokes formed an energy reservoir that was thermalized to the high kinetic temperatures observed. Ion kinetic temperatures up to 2.5 keV have been measured in deuterium. The thermal velocity of these hot ions was proportional to the spoke rotational velocity [34]. Previous work [34] has shown that the ion population can be heated equally well by positive or negative electrode polarities. However, investigations reported in ref. 35 indicate that the polarity of the electric field has a profound effect on the density and particle confinement time.

1.2. Characteristics of the NASA-Lewis EFBT experiment

The Electric Field Bumpy Torus (EFBT) plasma was generated in the NASA-Lewis Superconducting Bumpy Torus Magnet Facility [36]. Gross confinement is provided by the bumpy torus magnetic field generated by twelve superconducting coils. An isometric cutaway drawing of the apparatus is shown in fig. 1. The twelve coils, each capable of three tesla on its axis, have a 19 cm inside diam-

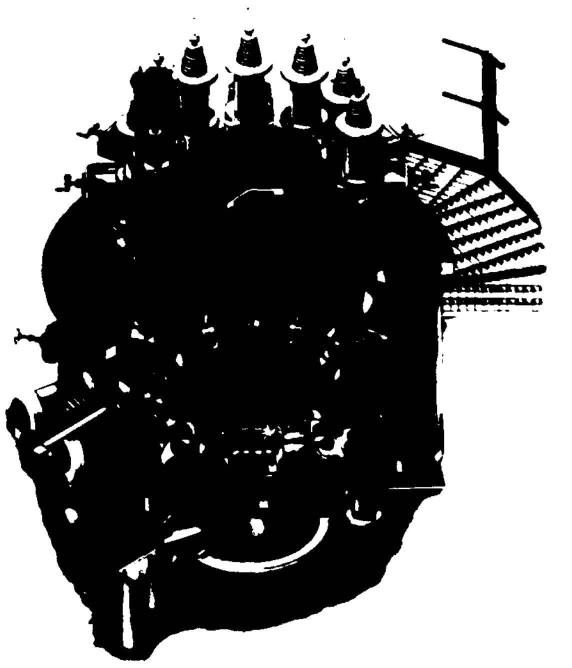


Fig. 1. Isometric cutaway drawing of the superconducting Bumpy Torus Magnet Facility.

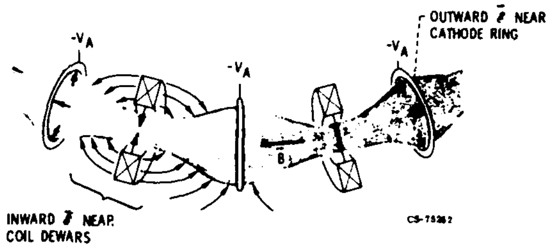


Fig. 2. Electric field structure in a bumpy torus plasma with negative midplane electrodes.

eter, and are arranged in a toroidal array 1.5 m in major diameter.

The entire toroidal ring of plasma can be biased to positive or negative potentials on the order of kilovolts by one or more electrodes located at the midplanes of 1 or more sectors of the toroidal array [33,34]. The electric field structure of an EFBT plasma with negative midplane electrodes is illustrated in fig. 2. Some biasing electrodes used with the EFBT plasma are illustrated in fig. 3. These electrodes either surround the minor circumference of the plasma, like the D-shaped electrode illustrated in fig. 3a, or pass directly through a minor diameter of the plasma, like the water-cooled tube illustrated in fig. 3b, or the tungsten wire illustrated in fig. 3c. The water-cooled electrodes have been fabricated of copper or stainless steel tubing. With a negative bias on these electrodes, they act like large Langmuir probes in ion saturation, and collect all ions produced in the toroidal plasma volume. The ions are carried radially inwards by fluctuation-induced transport over the remainder of the plasma surface, where the radial electric field points inward, creating a toroidal potential well for ions [37–40]. With opposite (positive) electrode polarity, the ions are transported outward by the same mechanism [37,38].

In fig. 4 is illustrated the radial potential profile in the EFBT plasma when a positive or negative potential of 10 kV was applied to the biasing electrode in an adjacent sector of the torus. The upper curve shows the radial potential profile with a positive bias of 10 kV, the lower curve corresponds to a negative bias of 10 kV. The radial electric fields reverse sign when the polarity of the basing voltage changes sign, and they exceed values of 1 kV/cm in the case illustrated. These very strong electric fields in the bulk of the plasma are maintained by beam–plasma interactions characteristic of EFBT plasmas in a modified Penning discharge configuration [41,42]. The floating potential of the plasma measured 2 and 4 sectors (60° and 120°, respectively) away from the floating Langmuir probe is shown in fig. 5. Some axial potential drop occurred for this condition, but the strongest electric field was radial, consistent with results from the modified Penning discharge [43].

Fig. 6 shows the functional dependence of the electrode current I_a, the Langmuir probe voltage proportional to the ion saturation current at the plasma boundary V_s, the Langmuir probe floating potential at the plasma boundary V_f, and the particle confinement time τ_p based on the average electron number density measured by the microwave interferometer. These data were taken for a single negatively biased stainless steel electrode like that illustrated in fig. 3b, with inward-pointing electric fields, and a background neutral gas pressure of 7.6×10^{-5} Torr of deuterium. Because

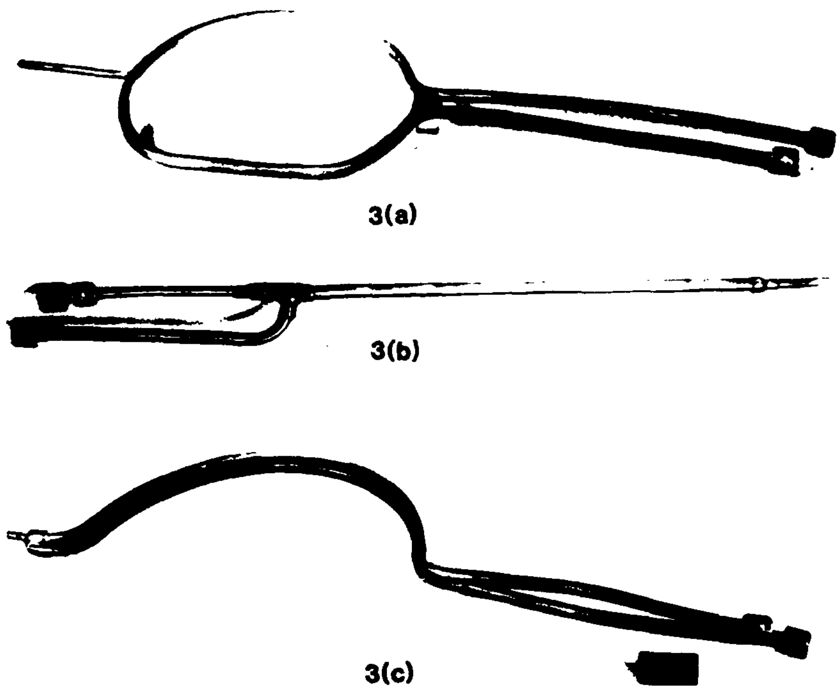


Fig. 3. Biasing electrodes used with EFBT plasma. (a) D-shaped electrode fabricated of watercooled copper tubing placed around the minor circumference of the plasma. (b) Stainless steel electrode fabricated from 6.4 mm diameter tubing which passes through a minor diameter of the toroidal plasma. (c) Electrode consisting of 10 mil. tungsten wire across the plasma minor diameter.

both the ion saturation current and the electrode current were linearly proportional to the average electron number density, the density profiles were probably geometrically similar over the range of number densities shown. The particle confinement time was almost independent of average number density over more than a factor of 50 variation in these quantities, and the floating potential varied relatively little over the same range.

The improved confinement possible with negative, as opposed to positive, bias can also be

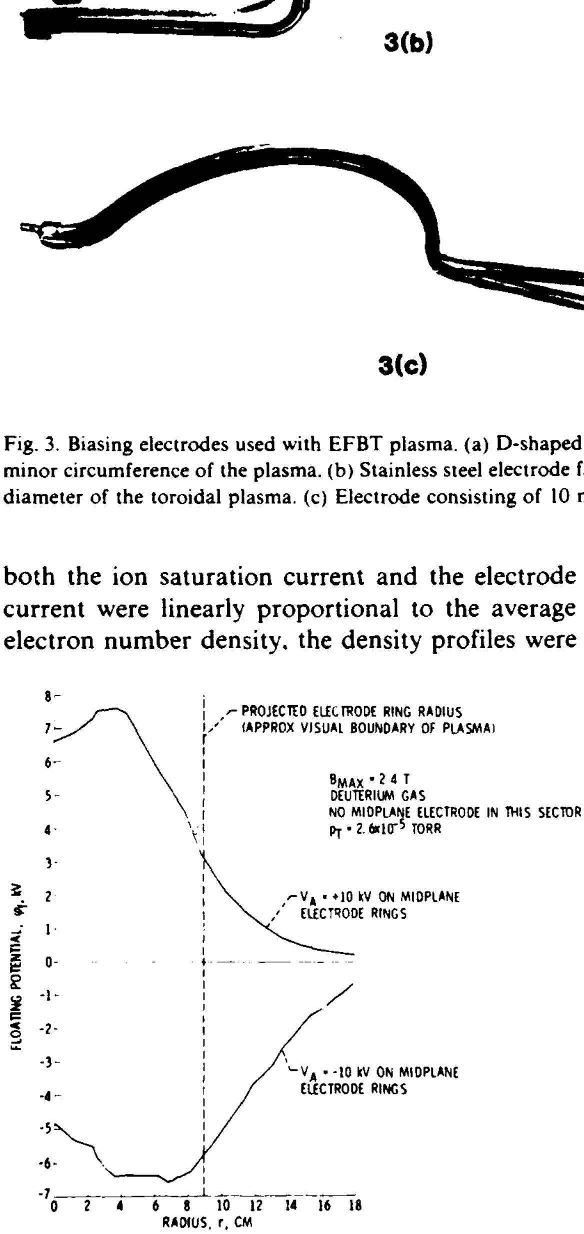


Fig. 4. Radial potential profile in the EFBT plasma for positive (*upper curve*) and negative (*lower curve*) potentials of 10 kV applied to the electrode rings.

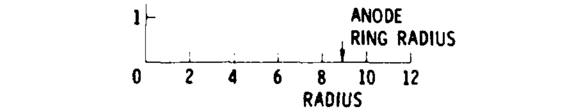


Fig. 5. Radial potential profile in the EFBT plasma for electrodes located 60° and 120° away from the sector where floating potential was measured.

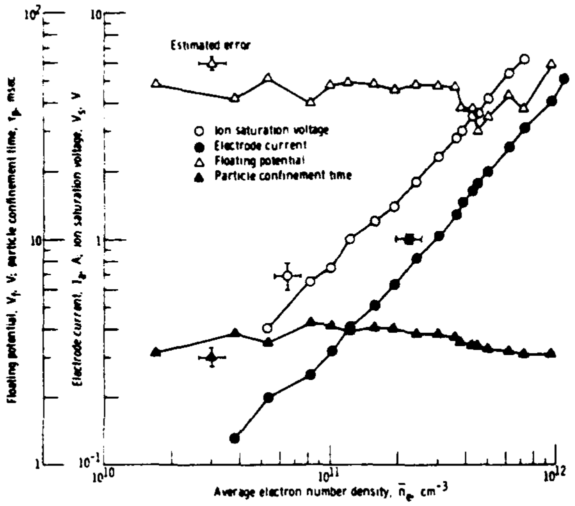


Fig. 6. Parametric variation of particle confinement time, floating potential, electrode current, and ion saturation voltage (relative ion number density) as functions of average electron number density-run series AJU.

exhibited in terms of average electron number density at a given electrode current. In fig. 7 the average number density is plotted as a function of

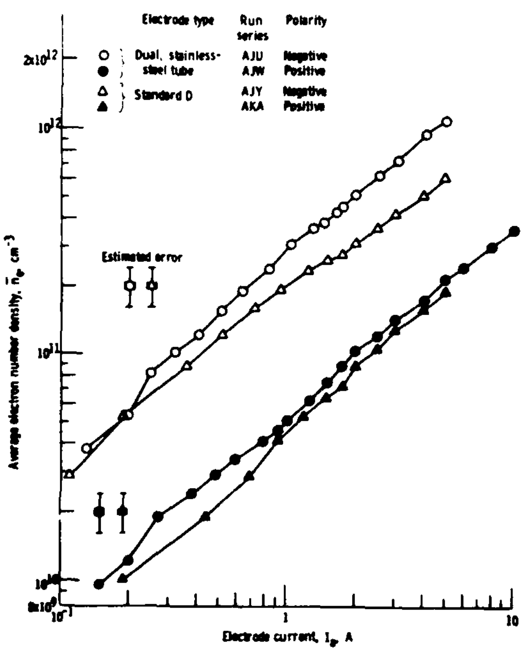


Fig. 7. Average electron number density as function of electrode current-run series AJW, AJU, AKA, and AJY.

electrode current for four sets of operating conditions. At a given electrode current, the average number density was at least 5 times higher with negative electrode polarity and an inward-pointing electric field than with positive polarity and an outward-pointing electric field. The improved confinement associated with the stainless-steel tube electrode was evident in that it produced number densities about 1.5 times higher than those of the standard D-shaped electrode. In addition, the average number density with the tube electrode was almost directly proportional to the electrode current, rather than tending to fall off with increasing electrode current as did the density with the standard D-shaped electrode. The electron number density was proportional to electrode current over the entire range investigated; only melting of uncooled sheet metal at the highest currents and densities limited the EFBT performance in this respect.

1.3. Plasma parameters

The characteristics of the EFBT plasma are shown in table 1 [40]. The highest *average* plasma density has been 3.1×10^{12} particles per cm^3, and the maximum density on the axis under these conditions has been about 6.2×10^{12} particles per cm^3. The *particle* containment time under these density conditions is 2.5 ms. The highest particle containment time has been observed at a somewhat lower average density, and has been as high as 6 ms. The highest simultaneous product of ion

Table 1
Characteristics of the Electric Field Bumpy Torus (EFBT) plasma.

Highest plasma densities:
$\bar{N}_e = 3.1 \times 10^{12}$ cm^{-3}
$\bar{N}_{e\,max} = 6.2 \times 10^{12}$ cm^{-3}, $\tau_p = 2.52$ ms
Highest particle containment time:
$\tau_p = 6.0$ ms at $N_{e\,max} = 1 \times 10^{12}$ cm^{-3}
Highest simultaneous $N_{e\,max}\tau_p$:
$N_{e\,max}\tau_p = 1.6 \times 10^{10}$ s/cm^3
Ion kinetic temperatures for deuterium:
for above conditions, $360 \leq T_i \leq 520$ eV
highest ever observed, $T_i = 2500$ eV
Electron kinetic temperatures:
for above conditions, $2 \leq T_e \leq 10$ eV
highest ever observed, $T_e = 150$ eV

number density and particle containment time has been about 1.6×10^{10} s/cm^3. For the average particle number density of 3.1×10^{12} per cm^3, the ion kinetic temperatures have ranged from about 360 to 520 eV. The highest ion kinetic temperature ever observed in deuterium gas was 2500 eV, and in helium was 3500 eV. The electron kinetic temperatures are very low, and for the above conditions range between 2 and 10 eV. The highest electron kinetic temperature has been about 150 eV. This very low electron temperature is characteristic of EFBT plasmas, and arises because the ions and electrons acquire their energy in crossed electric and magnetic fields. The drift velocity which both species acquire is equal to E/B, so the heavier species acquires the most energy.

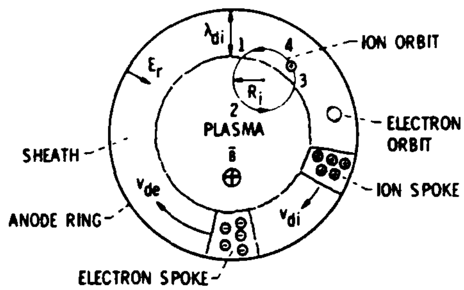


Fig. 8. Schematic minor cross section of EFBT plasma.

2. Ion heating and thermalization

A characteristic feature of the plasmas generated in the electric field bumpy torus configuration is the very low electron kinetic temperature, usually below 10 eV, accompanied by relatively high ion kinetic temperatures, which in some cases have equaled 2500 eV in deuterium. These relatively high ion kinetic temperatures are associated with a Maxwellian distribution of energies [33,34]. This large difference in the kinetic temperatures of the electron and ion population arises from the E/B drift mechanism by which the externally applied electric fields feed energy into the two populations. The dc radial electric fields along the minor radius of the plasma lead to an azimuthal drift of both ions and electrons which, to a first approximation, is independent of mass, charge, and the sign of the charge on these two species. This leads to the two species acquiring energies which differ by their mass ratio. The number densities achieved in this experiment (below 6×10^{12} particles per cm^3 on the plasma axis) are not sufficiently high to lead to ion–electron equilibration during the particle confinement times thus far achieved. The E/B drift velocities acquired by the ion lead to high monoenergetic energies, on the order of kilovolts, which are thermalized by the very high levels of electrostatic turbulence and fluctuations characteristic of this plasma.

The basic mechanism of ion heating in this plasma has been discussed previously, and is identical to that observed in the axisymmetric Penning discharge [29–32]. In fig. 8 is shown a schematic minor cross section of the plasma, in which the negatively biased plasma is confined in a cross section which passes through the grounded superconducting Dewars. This configuration leads to a radially inward electric field of the type illustrated in figs. 4 and 5, and a thick sheath in which the electric fields are much higher than ambipolar values. The electron orbits, because of their small gyroradii, will spend all of their time in the strong electric field of the sheath. The ions, however, because of their higher energies and large gyroradii, will on the average spend only a part of their time in the sheath. Thus, the ions will see a lower effective electric field than the electrons, and will tend to have an E/B drift velocity somewhat lower than that of the electrons. In this plasma, the ion drift velocities tend to be a factor of 5 to 10 lower than the electron drift velocities, apparently for this reason. The ions and electrons tend to bunch up into rotating spokes [29,30], a manifestation of the diocotron instability.

The relation between ion heating and spoke velocities has been investigated extensively in early experiments on the axisymmetric modified Penning discharge [29–32], and in more recent work on the electric field bumpy torus plasma [33,34]. It was shown that the ion kinetic temperature, measured by a charge exchange neutral energy analyzer and/or a retarding potential energy analyzer, was proportional to the energy that an ion would acquire by moving with the $\boldsymbol{E} \times \boldsymbol{B}/B^2$ drift velocity in the crossed electric and magnetic fields of the plasma. In refs. 29 and 30 a relation between the ion kinetic temperature and the frequency of the ion spoke was derived and is

$$\nu_s = \frac{1}{4\pi R}\sqrt{\frac{eT_i}{m_i}}, \tag{1}$$

where R is the inner radius of the midplane electrode rings, and T_i the ion kinetic temperature in eV. Eq. (1) was derived on the assumption that there is equipartition of energy among the three degrees of freedom of ion motion and the spoke velocity, and that the ion spoke velocity corresponds to the velocity of the most probable energy in a Maxwellian distribution of ion energy. Eq. (1) has been amply confirmed in the experimental observations cited above, and demonstrates the intimate relation between the externally applied radial electric fields, and the ability to raise the ion kinetic temperatures to kilovolt levels in these modified Penning discharge and EFBT plasmas.

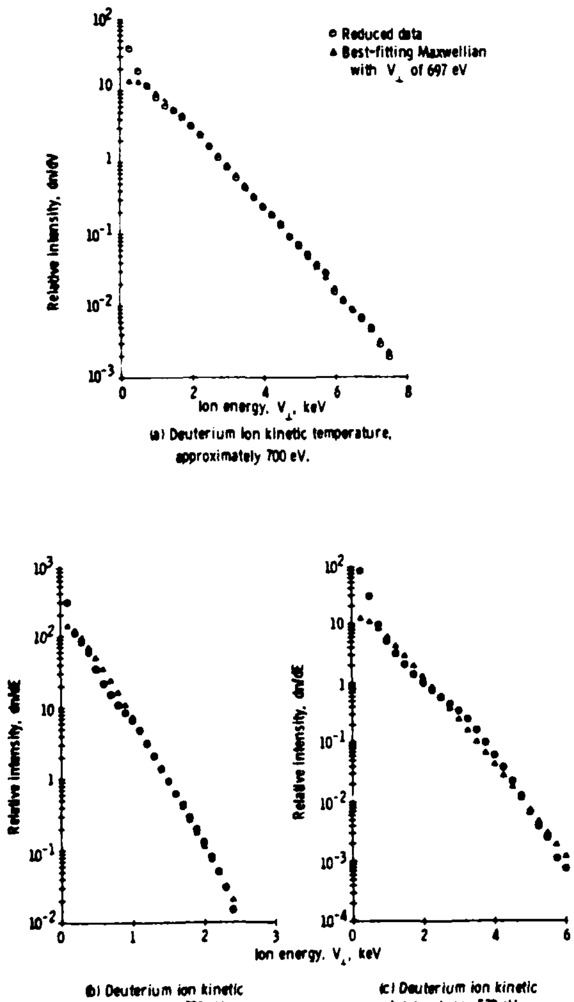


Fig. 9. Characteristic examples of highly Maxwellian ion energy distribution functions in the EFBT plasma.

Some characteristic examples of ion energy distribution functions taken from the EFBT plasma are shown in fig. 9. Fig. 9a shows an ion energy distribution function for deuterium gas with a negatively biased electrode, radially inward electric fields over the plasma surface, and plasma electron number densities about $5 \times 10^{11}/\text{cm}^3$. The reduced data from a charge exchange neutral energy analyzer are shown by the open circles, and the best-fitting Maxwellian distribution with an ion kinetic temperature of approximately 700 eV is shown by the triangular symbols. This distribution function is remarkable not only for the degree of Maxwellianization, but also for the great distance into the Maxwellian tail over which the distribution remained so – over 9 energy e-folding lengths. Fig. 9b shows an ion energy distribution function taken under operating conditions similar to those of fig. 9a but at an electron number density about 20% of the previous value. In this case, the ion kinetic temperature was approximately 220 eV, and the distribution again remained Maxwellian over 9 energy e-folding lengths. Fig. 9c had an ion kinetic temperature of 530 eV that departed slightly from a Maxwellian distribution. In this case, the applied electrode voltage (2 kV) was well within the region covered by the data. The presence of the electrode caused no perturbations in the distribution function, such as might result if the particles were accelerated in a sheath surrounding the electrode. The high degree of randomness exhibited by this plasma suggests that coherent phenomena, which might serve as reservoirs of free energy to drive instabilities, were minimized.

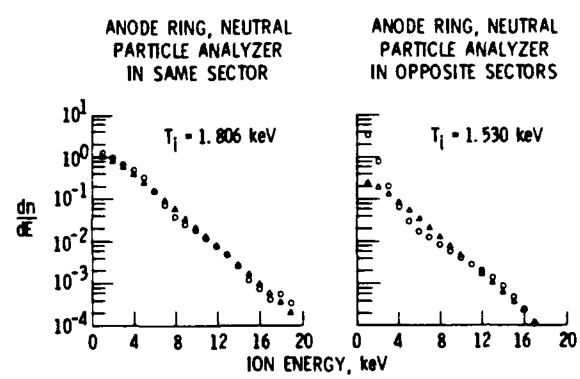


Fig. 10. Ion energy distribution functions measured with the neutral particle energy analyzer in the same sector and with the neutral particle energy analyzer at the opposite end of a major diameter from the biasing electrode.

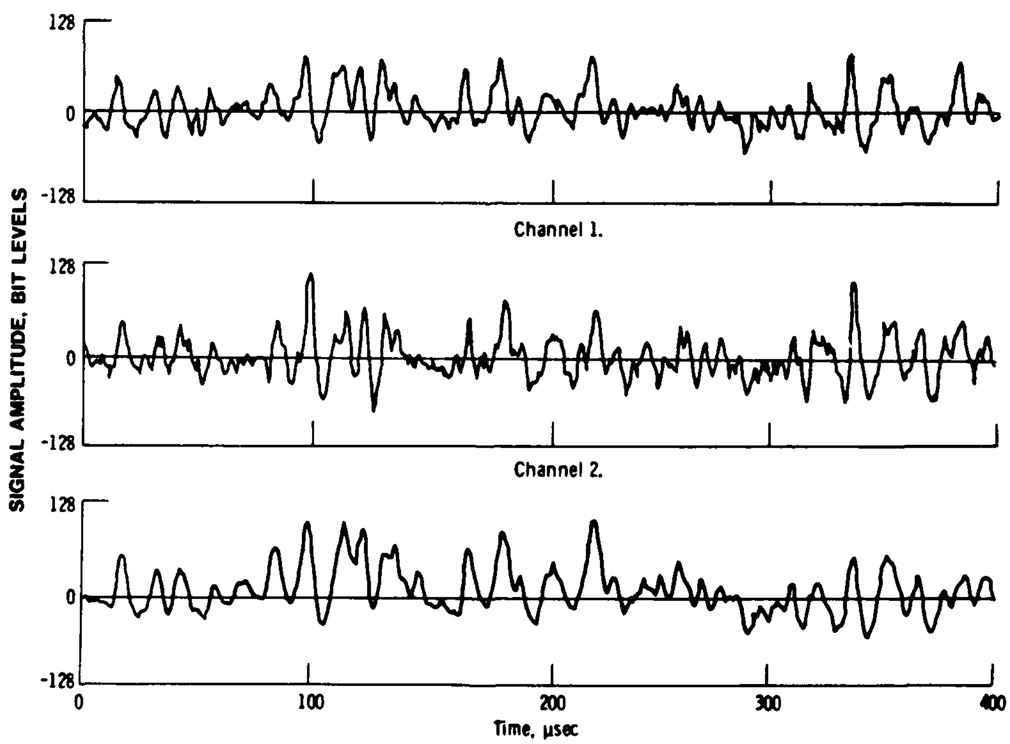
It was found that the ion heating process occurred in all twelve sectors of the NASA Lewis EFBT plasma, even when the plasma was biased by a single electrode in one sector. A paired comparison was performed, illustrated in fig. 10. The ion energy distribution functions were measured with a charge exchange neutral energy analyzer in sector 9 of the torus. The plasma was first generated by a single electrode ring in the sector in which the neutral particle analyzer was located, and then it was generated with an electrode ring located in sector 3, across the major diameter of the torus. During these latter measurements, a metallic baffle plate was installed on the major axis of the tank to prevent charge exchange neutrals originating at the opposite side of the torus from reaching the neutral particle analyzer [34]. In fig. 10a is the ion energy distribution function observed when the electrode ring and the neutral particle analyzer were both in sector 9 of the torus. In fig. 10b is the distribution function taken for the same operating conditions but with a single electrode ring located at the opposite major diameter of the torus, in sector 3.

An interesting implication of the data in fig. 10 is that the ions were being heated in each and every sector all around the torus, since the neutral particle energy analyzer only responds to ions with perpendicular velocities in the sector in which it located. It is highly unlikely that hot ions generated in another sector would undergo at least two scatterings, required to transport it from the sector of origin into the entrance slit of the neutral particle energy analyzer.

3. Plasma fluctuations and turbulence

3.1. Data sampling

A characteristic example of density and potential fluctuation spectra that were obtained from the electric field bumpy torus plasma are presented in this section. The experimental run



Channel 3.

Fig. 11. Simultaneously sampled waveforms of floating potential on capacitive probes (channels 1 and 2) and of density fluctuations measured with biased Langmuir probe (channel 3).

selected for illustration in the figures given below is run AJH-2, which was taken with negative electrode polarity and the radial dc electric field pointing into the plasma. This run is characteristic of the highly turbulent operating conditions which can be observed with both electrode polarities.

It was not possible to leave the probe assembly in the plasma continuously because damage to the capacitive and Langmuir probes would have resulted from plasma bombardment. During these investigations, the probe assembly was inserted in the plasma for approximately 0.3 s. The average plasma electron number density for run series AJH-2 was $5.4 \times 10^{11}/\text{cm}^3$. The spectra presented below were computed from a time series consisting of 2048 8-bit samples taken every 1 μs. The duration of each record was 2.048 ms, and the Nyquist frequency was 500 kHz. This approximately 2 ms data window was taken at the 150 ms point during the dwell time of the probe in the plasma. The spectral plots were frequency averaged over 9 elementary frequency bands, for a spectral bandwidth of 4.39 kHz. A cosine-bell data window was applied to the raw time-series data in order to minimize the effects of leakage.

3.2. Fluctuation waveforms

Fig. 11 illustrates the nature of the raw time-series data from which the fluctuation spectra were computed. Channels 1 and 2 are the simultaneously sampled potential waveforms from the capacitive probes. Channel 3 is the simultaneously sampled ion saturation current flowing to the biased Langmuir probe. The 8 bit amplitude capability of the waveform recorders corresponds to 256 intervals. The absolute amplitudes corresponding to these intervals are determined by the settings of the waveform recorder and other instruments in the data-handling system [38–40]. The abscissa shows the data points from the first 400 of the 2048 data samples. These waveforms therefore cover approximately 20% of the data in each channel that were used to compute the fluctuation spectra discussed here.

The data in fig. 11 were taken for negative polarity conditions that resulted in a turbulent plasma without discrete peaks in the spectra. Careful examination of the signals in channels 1 and 2 shows that the signal in channel 1 was slightly delayed with respect to the signal in channel 2, as the result of E/B drift of the plasma.

3.3. Fluctuation spectra

The physics information that can be obtained from the fluctuation-induced plasma transport diagnostic is illustrated by an experimental run in fig. 12. This figure consists of eight computer-generated spectra. Spectrum (A) is the autopower spectrum of $\tilde{\phi}_1(t)$. All system calibration factors have been taken into account, so that the ordinate of each data point corresponds to the mean-squared value [i.e., $\phi^2_{\text{rms}}(\omega)$] of the potential fluctuations over a 4.39 kHz spectral bandwidth. Spectrum (B) is the autopower spectrum of the density fluctuations, with each point denoting the mean-squared value [i.e., $n^2_{\text{rms}}(\omega)$] of density fluctuations over a 4.39 kHz spectral bandwidth.

Spectra (C) and (D) are both phase spectra. Spectrum (C) corresponds to the phase spectrum $\theta_{12}(\omega)$ of the cross power spectrum computed from $\tilde{\phi}_1(t)$ and $\tilde{\phi}_2(t)$. From the phase spectrum $\theta_{12}(\omega)$ the wave number $k_\theta(\omega)$ can be readily determined [13,14]. From $k_\theta(\omega)$ the azimuthal phase velocity $\omega/k_\theta(\omega)$ can be computed. Generally, the phase velocities associated with the $\theta_{12}(\omega)$ were about 10^6 cm/s. This is within a factor of 2 of the E_r/B drift, where E_r – the static, radial electric field resulting from the dc voltage applied to the electrodes – was about 100 V/cm and B – the toroidal magnetic field at the point at which the measurements were being made – was 0.67 T.

Spectrum (D), the phase of the cross-power spectrum computed from $\tilde{\phi}_1(t)$ and $\tilde{n}(t)$, represents the phase difference $\alpha_{n\phi}(\omega)$ between the density and potential fluctuation on a spectral basis. Spectrum (E), the squared coherency spectrum between channels 1 and 2, measures the relative degree of coherence between the electrostatic potential fluctuations sampled by the two capacitive probes. Spectrum (F), the square of the degree of mutual coherence $(|\gamma_{n\phi}(\omega)|)^2$ between channels 1 and 3, measures the degree of linear relationship between the density and potential fluctuations.

Spectrum (G) is the transport spectrum $T(\omega)$ [37–40]. The transport spectrum $T(\omega)$ is a real quantity and may be either positive or negative, indicating that the transport is in either the inward or outward direction, respectively. Two quantities

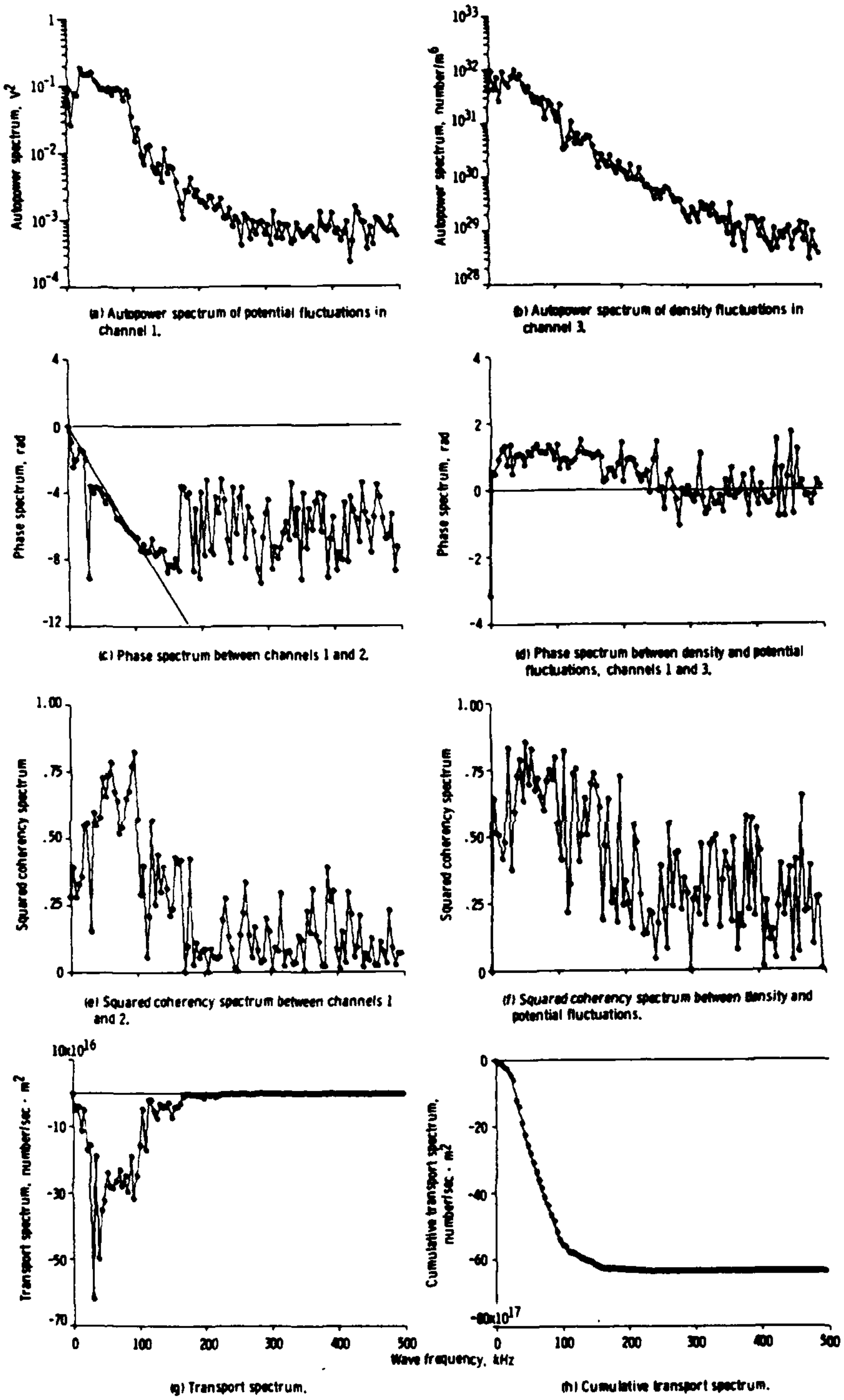


Fig. 12. Computer-generated spectra over frequency range 0–500 kHz-run AJH-2.

determine the sign of $T(\omega)$ and hence the direction of transport. The first quantity is the phase difference $\alpha_{n\phi}(\omega)$ between density and potential fluctuations. If $\alpha_{n\phi}(\omega)$ changes sign, $T(\omega)$ changes sign, since $T(\omega)$ is proportional to $\sin \alpha_{n\phi}(\omega)$. The second quantity determining the sign of $T(\omega)$ is

the sign of $k_\theta(\omega)$, which in turn is determined by the direction of wave propagation in the azimuthal direction. Spectrum (H), the cumulative transport spectrum, was found by summing the transport spectrum $T(\omega)$ from zero frequency to the frequency on the abscissa. The cumulative transport at 500 kHz is the total fluctuation-induced transport associated with the fluctuation spectrum extending from 0 to 500 kHz.

Fig. 12 shows the fluctuation spectra for run AJH-2, which had negative electrode polarity. This run was characterized by turbulence. No discrete peaks are apparent in the spectra of either the potential or density fluctuations (figs. 12a and b). The coherence (figs. 12e and f) was relatively low, and the transport was spread over a broad range of frequencies to 120 kHz. The entire turbulent mass of plasma rotated with a common velocity in the E/B direction and with a negative slope, as is evident in the phase spectrum (fig. 12c). The dispersion relation was linear to 120 kHz.

3.4. Amplitude statistics

One method of determining the degree of randomness in the fluctuation data is to compare it against Gaussian random noise as a standard. This was done by taking the raw waveform amplitudes for density and potential fluctuations, such as those shown in fig. 11, and apportioning the amplitudes among 30 positive and 30 negative discrete bins, which were used to form cumulative probability distributions. The second through fourth moments of the cumulative probability distribution were calculated, and the resulting values for the illustrative run AJH-2 listed in table 2. Skewness, a normalized third moment of a probability distribution function, measures the degree of asymmetry about the mean value. For a Gaussian distribution the skewness is zero. Kurtosis, a normalized fourth moment of a probability distribution function, measures the degree of broadening of the distribution function about the mean value. For a Gaussian distribution, the kurtosis is 3.0.

Table 2 shows the moments of the cumulative

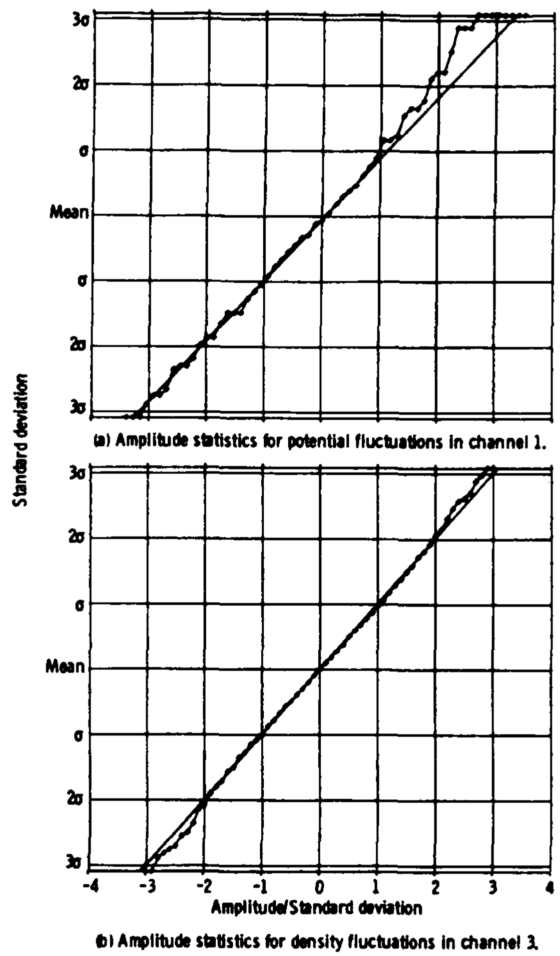


Fig. 13. Amplitude statistics plotted on probability paper, with amplitude normalized with respect to standard deviation-run AJH-2.

Table 2
Amplitude statistics and spectral indices of illustrative experimental run.

Operating condition	Experimental run AJH-2
Standard deviation:	
Channel 1 (V)	1.6
Channel 2 (V)	2.4
Channel 3, particles/m^3	3.6×10^{16}
Skewness:	
Channel 1	−0.22
Channel 2	−0.07
Channel 3	0
Kurtosis:	
Channel 1	2.8
Channel 2	2.9
Channel 3	2.7
Spectral index, p:	
Channel 1	2.5
Channel 2	2.7
Channel 3	3.8

probability distributions for the potential and density fluctuations of run AJH-2. They are consistent with the impression that the spectra shown in fig. 12 exhibit Gaussian random turbulence.

Fig. 13 shows the cumulative probability distributions of the potential and density fluctuations, respectively, of run AJH-2. The corresponding fluctuation spectra, shown in fig. 12, indicate turbulence. In this case, because the cumulative probability plots approximate a straight line, the amplitude statistics are shown to be Gaussian.

3.5. Spectral index

Previous investigation of plasma turbulence in a modified Penning discharge operated in an axisymmetric magnetic mirror geometry [32] revealed that the background electrostatic turbulence in such a plasma tended to obey a power law of the general form

$$P(\omega) \propto \omega^{-p}, \tag{3}$$

where ω is the frequency and p is the spectral index. Available theories of plasma turbulence, cited in ref. 32, predict a spectral index of 5.0. The results reported in ref. 32 show that the spectral indices differed greatly from the predicted value of 5.0.

For this plasma, in which drift waves were not observed, the frequency spectra of the potential and density fluctuations shown in figs. 12 and 13 were plotted on log–log paper to exhibit the extent to which the spectra had a power law form. One such result, for run AJH-2, was plotted in fig. 14, where part a is the spectrum of potential fluctuations in channel 1, and part b is the spectrum of density fluctuations in channel 3. These data were turbulent and had Gaussian amplitude statistics, with no prominent peaks at low frequencies. The data are characteristic in that the density and potential fluctuations had different spectral indices. This is consistent with the findings of ref. 32 that the spectral index different when electrostatic

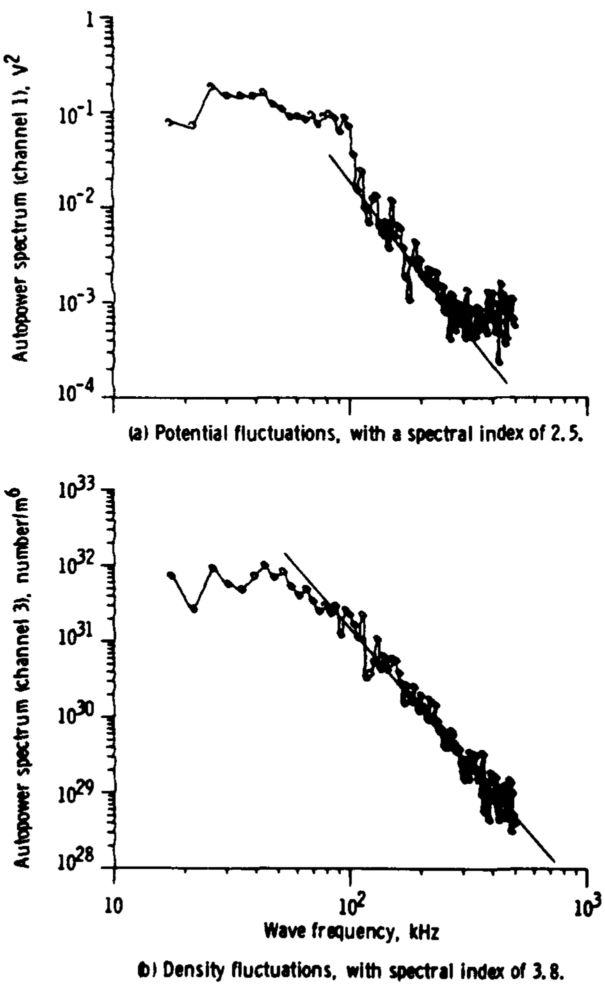


Fig. 14. Amplitude spectrum of potential and density fluctuations plotted on log–log paper to exhibit power-law dependence of amplitude spectrum at high frequencies-run AJH-2.

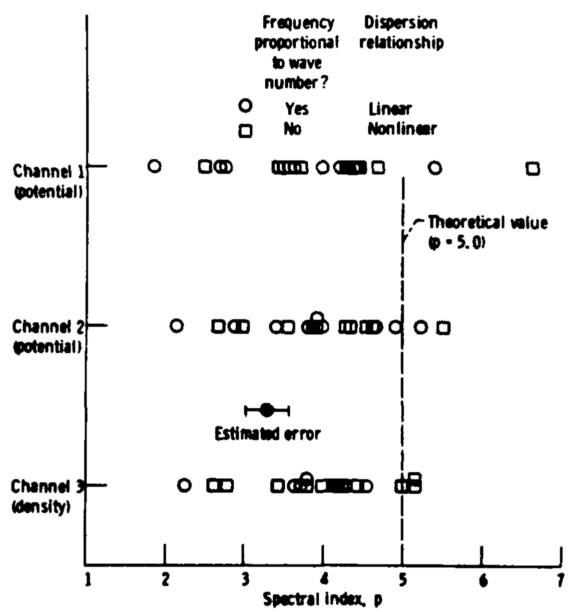


Fig. 15. Scatter plot of spectral indices of characteristic experimental runs. The runs with round symbols had a linear relationship between frequency and wavenumber up to about 100 kHz; the data with square symbols did not.

potential fluctuations were sampled at two different locations within the same plasma. This may be an indication of the inhomogeneous nature of the observed turbulence.

The spectral indices for the two potential fluctuation spectra and the one density fluctuation spectrum are given in table 2 for run AJH-2. Seventeen additional experimental runs were reduced and their fluctuation spectra plotted on log–log paper. These are plotted in fig. 15. Most of these were turbulent, with no prominent spectral peaks. No systematic trend of spectral index with operating parameters was evident. In fig. 15, the spectral index of the density and potential fluctuations ranged from 2 to 6.

4. Fluctuation-induced radial transport

4.1. Diagnostic system

The radial flux of ions in this plasma was measured with a transport diagnostic based on a physical model which assumed such low-frequency ($\omega \ll \omega_{ci}$) electrostatic potential fluctuations that a particle's fluctuating velocity could be modeled in terms of $\tilde{E}/B$ drift, where $\tilde{E}$ is a fluctuating electric field and B is the static, confining toroidal magnetic field [44]. The time-averaged particle flux was then given by

$$\Gamma = \tilde{n}\tilde{v} = \tilde{n}\tilde{E}/B, \tag{3}$$

which can also be expressed in terms of a transport spectral density function $T(\omega)$ as

$$\Gamma = \tilde{n}\tilde{v} = \int_0^\infty T(\omega)\mathrm{d}\omega. \tag{4}$$

Ref. 44 shows that the transport due to a small band of frequencies $\delta\omega$ centered at ω is given by $T(\omega)$ and is equal to

$$T(\omega)\delta\omega = \frac{k(\omega)}{B} n_{\mathrm{rms}}(\omega)\phi_{\mathrm{rms}}(\omega) \sin \alpha_{\mathrm{n}}(\omega)|\gamma_{\mathrm{n}}(\omega)|. \tag{5}$$

To relate the potential $\tilde{\phi}$ and electric field $\tilde{E}$ fluctuations, we assumed an electrostatic approximation $\tilde{E} = -\nabla\tilde{\phi} = \mathrm{i}k(\omega)\tilde{\phi}$. The transport associated with $T(\omega)$ depends on the product of the rms values of density n_{rms} and potential ϕ_{rms} fluctuations, the sine of the phase angle $\alpha_{\mathrm{n}}(\omega)$ between the density and potential fluctuations, and the degree of mutual coherence $|\gamma_{\mathrm{n}}(\omega)|$ between the potential and density fluctuations in the spectral band under consideration. The wave number $k(\omega)$ appears since the electrostatic approximation was assumed. The transport spectrum $T(\omega)$ is a real quantity and may be either positive or negative, depending on whether the transport is inward or outward.

To implement this transport diagnostic, it was necessary to develop a data acquisition system that could simultaneously acquire and digitize density and potential fluctuation data and transfer the raw time-series data to a computer for processing. Expressing all spectra of interest (particularly the transport spectra) in absolute physical units required knowledge of the system calibration data (e.g., voltage range settings on the digitizer, preamplifier gain settings, etc.). The system used to acquire and process the data discussed in this paper is described in ref. 45.

4.2. Dependence of confinement and transport on electrode polarity

The effect of the direction of the electric field on particle confinement time and electron number density is shown in the paired comparison experiment illustrated in fig. 16. The only conditions

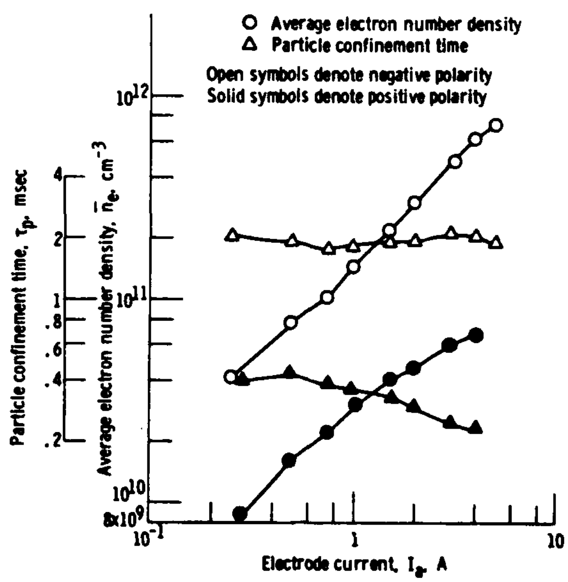


Fig. 16. Average electron number density and particle confinement time as functions of electrode current for positive and negative electrode polarity-run series AHN 1-9 and AHN 18-25.

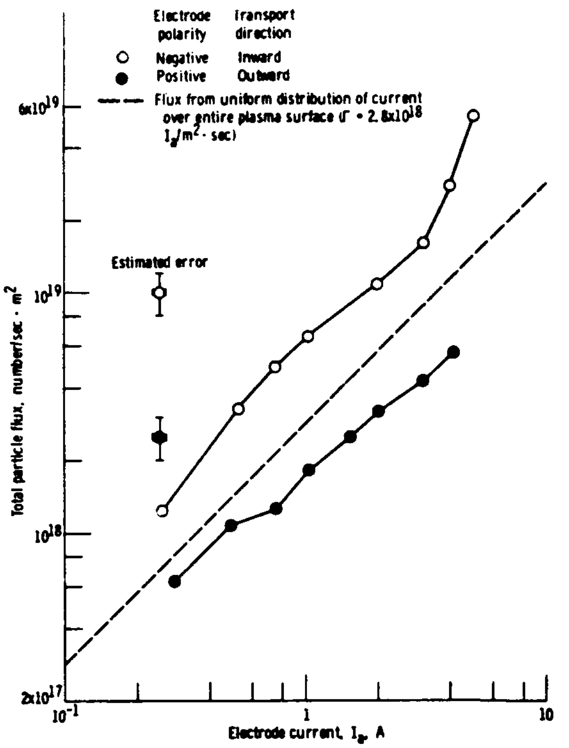


Fig. 17. Total particle flux for positive and negative electrode polarity as function of electrode current-run series AHN 1–9 and 18–25.

that differed were the polarity of the two midplane electrode rings used and the geometric position of the midplane electrodes, which was optimized for each polarity [35–40]. The solid symbols represent positive polarity, for which the radial electric field points (and pushes ions) radially outward. The open symbols represent negative polarity, for which the radial electric field points (and pushes ions) radially inward. Both the particle confinement time and the average electron number density were at least five times higher when the radial electric field pointed inward than when it pointed outward.

In fig. 17 is illustrated the fluctuation-induced ion flux measured at the boundary of the EFBT plasma, as a function the electrode current flowing to the plasma. The upper curve with open data points shows the radially inward ion flux usually observed with negative biasing potentials on the electrodes. Stochastic processes such as fluctuation-induced transport and plasma turbulence allow these ions to fall down the potential well to the center of the plasma, against the density gradient. The total particle flux, in ions per square meter per second, is shown on the ordinate, and the current flowing to the electrode is shown on the abscissa. The lower curve, with solid data points, represents the opposite (positive) bias on the EFBT plasma, in which the electric fields are pointing radially outward. In this case, the ions are driven outward along a minor radius of the plasma.

For both electrode polarities, the radial transport increased with increasing electrode current in an almost linear manner. This linear proportionality implies that the fluctuation-induced radial transport measured by this diagnostic technique was the dominant radial transport process in this plasma over the entire range of electrode current for which data were taken. If fluctuation-induced transport made a minor contribution to the total electrode current, and hence to the total particle losses from the plasma, the electrode current would vary independently of the radial ion flux.

Another significant observation was that the ion fluxes were in good *quantitative* agreement with the observed electrode currents. The relationship between the electrode current and the particle flux can be written as

$$I_a = e\Gamma A_P, \tag{6}$$

where A_p is the surface area of the plasma at the probe radius, which for the bumpy torus plasma was approximately 2.2 m^2. The dashed line in fig. 17 shows the relationship between particle flux and electrode current which would be expected if the current flowing to the electrodes was evenly distributed over the entire surface of the plasma. The current to the power supply which energizes the EFBT plasma is maintained by ions which are collected by the negative electrodes and by the electrons collected by the positive electrodes. The fact that the observed particle fluxes were within about a factor of 1.5 of this theoretical straight line is remarkable and indicates that there was good quantitative as well as qualitative agreement between the measured particle fluxes and the total electrode current flowing from the plasma to the power supply.

Fig. 18 shows four characteristic transport spectra that correspond to an electrode current of 0.75 A, which is plotted in figs. 16 and 17. There are two spectra for negative electrode polarity and two for positive electrode polarity. In each case the upper graph is the transport spectrum $T(\omega)$, and the lower graph is the ion cumulative transport up

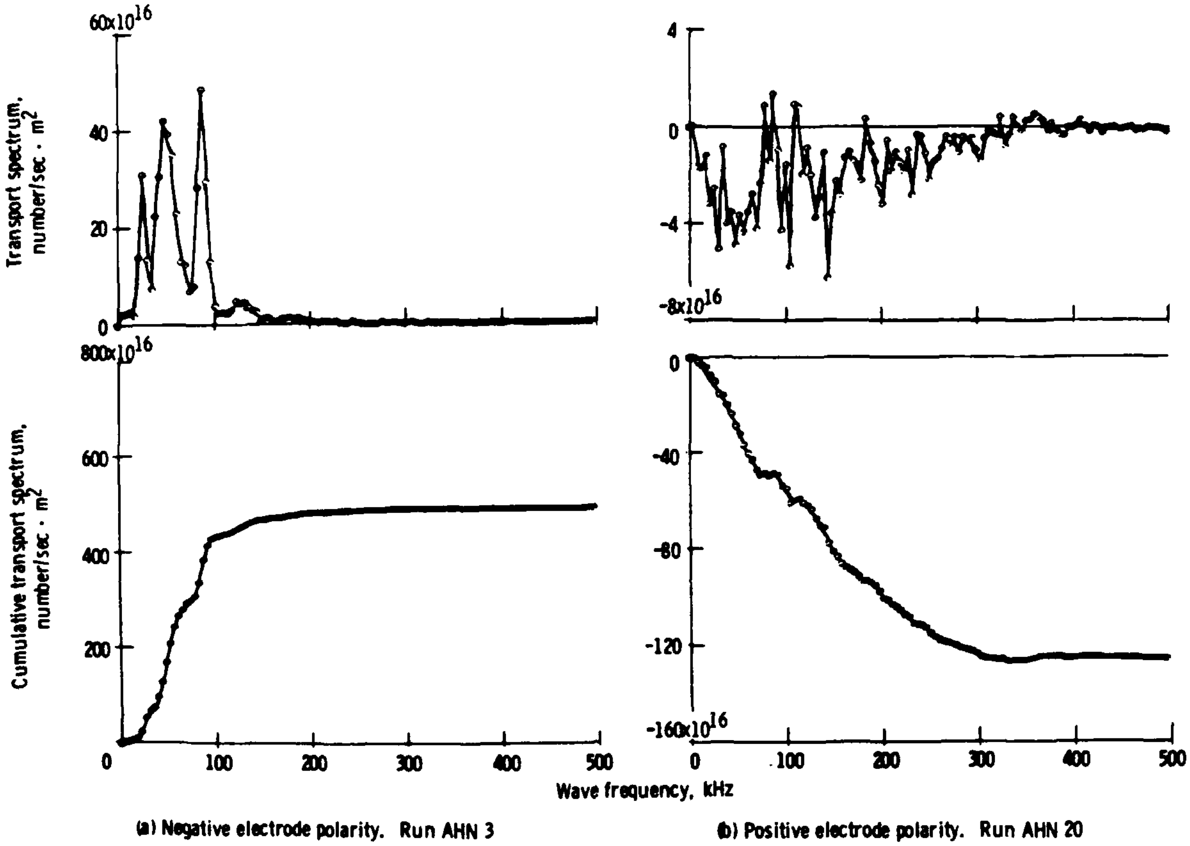


Fig. 18. Characteristic transport and cumulative transport spectra for electrode current of 0.75 A.

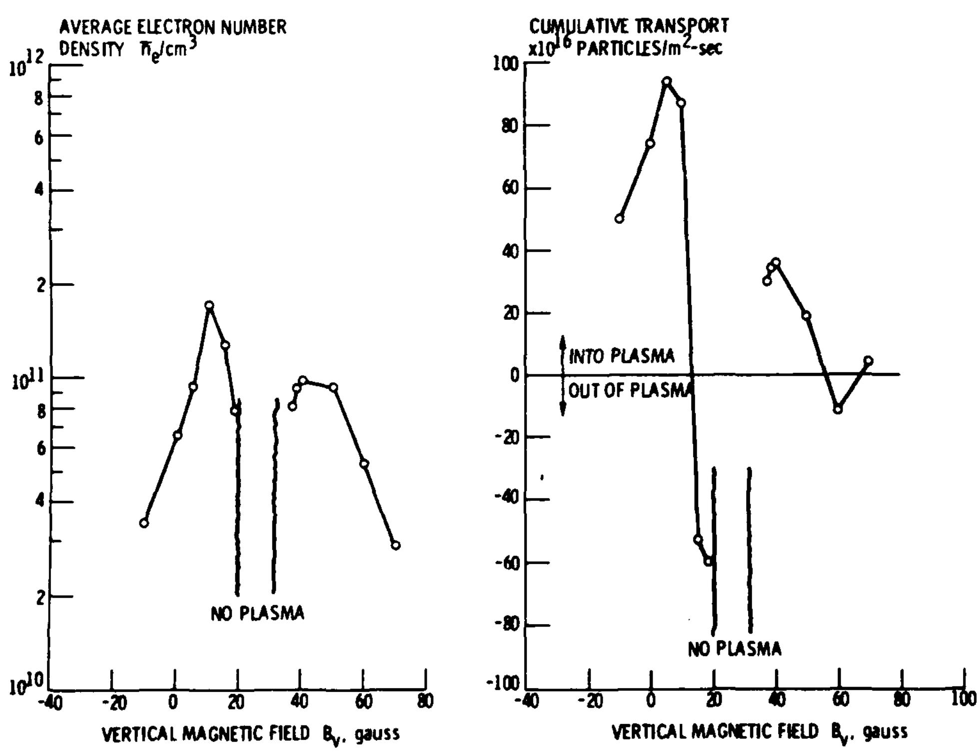


Fig. 19. Effect of weak, vertical magnetic field on confinement-run series AHF 13-24.

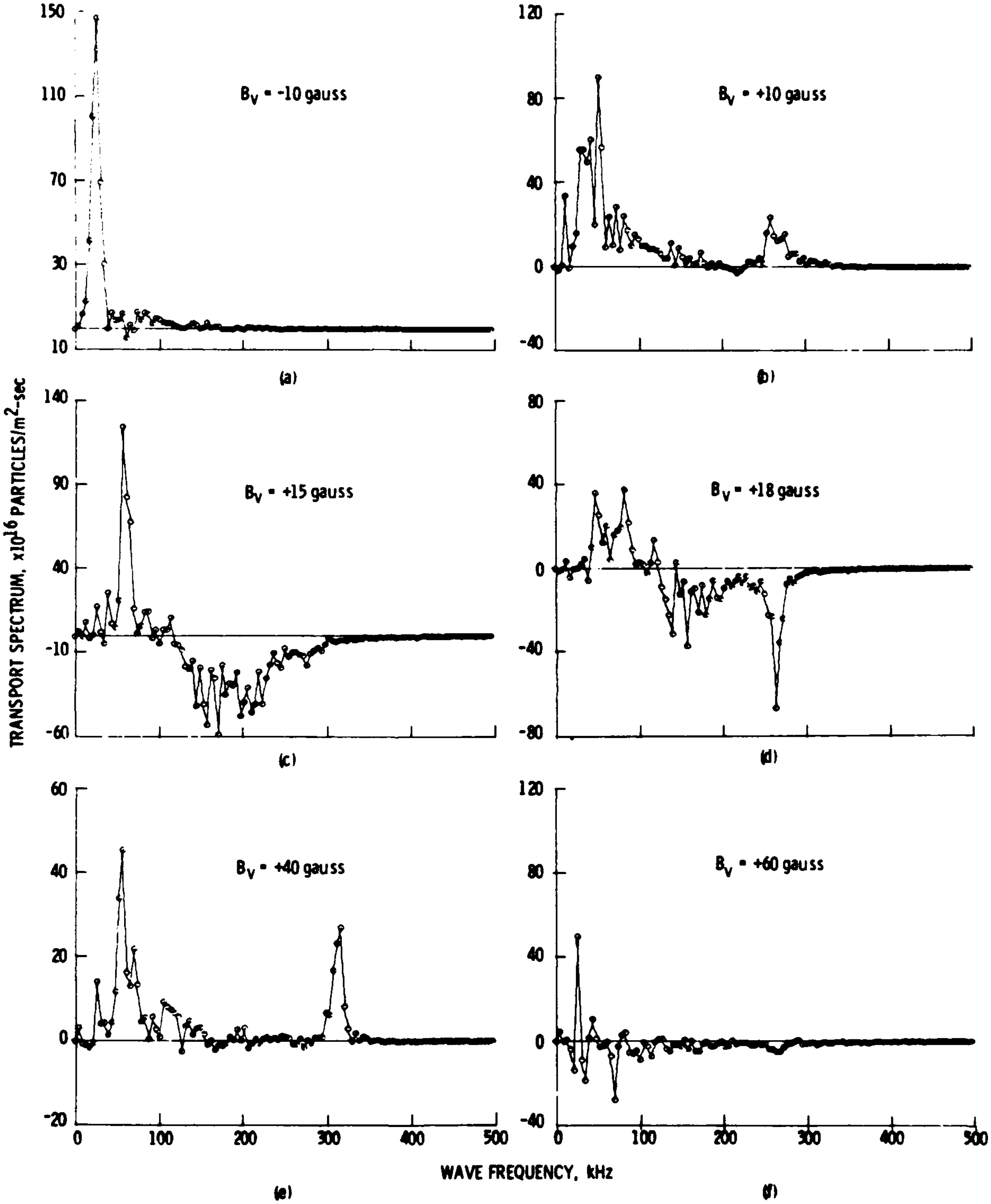


Fig. 20. Radial transport spectra for six vertical magnetic fields B_v.

to the frequency shown on the abscissa. In fig. 18a, the negative electrode with a radially inward-pointing electric field has a transport spectrum that is positive in sign, indicating radially inward transport. The transport is associated with three discrete peaks below 150 kHz. For this condition, the ion flux was radially outward in the sheaths that surrounded the negative electrodes, and the net ion confinement was a balance between infusion in the empty sectors and losses in the sectors with electrode rings. In fig. 18b, the positive electrode has a transport spectrum that is negative in sign, indicating radially outward transport toward the surrounding walls. This outward transport occurred over a broad frequency band out to 350 kHz and could be considered "turbulent transport".

4.3. Radial transport as a function of a weak vertical magnetic field

The particle confinement time and average electron number density in this plasma were extraordinarily sensitive to a weak vertical magnetic field, about one-thousandth of the toroidal magnetic field, applied to the confinement volume. These vertical fields were generated by two coils wrapped around the exterior of the vacuum tank and ranged over ± 0.01 T (positive is upward). The effect of this vertical magnetic field on the average electron number density is shown in fig. 19a. When these data were taken, electrode voltage, deuterium background pressure, maximum magnetic field, and other independent variables were held constant at the negative polarity operating conditions in figs. 16–18. There was a region between 2 and 3.2 mT in which no plasma could be generated. The effect of vertical magnetic field on the ion flux at the probe location is shown in fig. 19b. The vertical magnetic fields that resulted in the highest inward transport of ions corresponded to the highest electron number densities, and the vertical magnetic fields that resulted in the highest outward transport of ions corresponded to the lowest electron number densities, where the plasma is approaching extinction.

The transport spectral density function for six values of the vertical magnetic field plotted in fig. 19 is shown in fig. 20 in absolute units for frequencies up to 500 kHz. When the vertical magnetic field was -1 mT, the radially inward transport was dominated by a large peak at 20 kHz. As the vertical magnetic field was increased to $+1$mT, inward transport was found over broad, almost turbulent, spectrum from 0 to 150 kHz, and a peak of inward transport also appeared at about 250 kHz. As the vertical magnetic field was increased to 1.5 and 1.8 mT, which are near the region of plasma extinction in fig. 19, the transport near 250 kHz reversed direction and flowed radially outward. The area under the curve in this portion of the spectrum dominated the total transport and resulted in net outward transport of ions. Beyond the region of plasma quenching from 2 to 3.2 mT, two major peaks at a vertical field of 4 mT dominated the transport and were radially inward. As the vertical magnetic field was further increased to 6 mT, the importance of the high-frequency peak diminished and the total transport rate became much smaller in magnitude.

Spectral plots like those in fig. 12 show that the direction of transport associated with the peak near 250 kHz in fig. 20 was reversed because the phase angle between density and potential fluctuations, $\alpha_{n\phi}$, changed sign as the vertical magnetic field was changed from run to run. As is indicated by eq. (5), a change in sign of the phase angle $\alpha_{n\phi}$ results in a change in the direction of fluctuation-induced transport.

5. Confinement time scaling

5.1. Physical model

A series of calorimetric and other investigations [40,45] showed that no parasitic currents were flowing outside the plasma volume or directly along the magnetic field lines that might short circuit the power supply to ground, and that no ambipolar currents were flowing to either electrode. The latter condition implies that the cathode did not emit electrons and that all ion-electron pairs were created by volume ionization within the bulk of the plasma. The calorimetric measurements showed that parasitic or ambipolar currents contributed no more than 1% to the current flowing to the power supply [45].

Under these conditions, the direct current flowing to the power supply was a measure of the charge losses of the plasma, with all ions flowing to the cathodes and all electrons flowing to the

anodes. The total power supply current to this steady-state plasma can be written

$$I_a = \bar{n}_e e V_P/\tau_p \ [\mathrm{A}], \tag{7}$$

where $\bar{n}_e$ is the average number density measured by the microwave interferometer, e is the electronic charge, V_P is the plasma volume (82 l for the Lewis EFBT plasma), and τ_p is the overall particle confinement time. Eq. (7) can be rearranged to yield

$$\tau_p = \bar{n}_e e V_P/I_a \ [\mathrm{s}], \tag{8}$$

so that the particle confinement time can be calculated from the average number density measured by the microwave interferometer, and the direct current flowing to the power supply.

The electrode current I_a carried by ions that flow across electrode sheaths of total area A with current density J_a can be written

$$I_a = J_a A = \tfrac{1}{4} e n_s v_i \ [\mathrm{A}], \tag{9}$$

where n_s is the ion number density at the outer boundary of the sheath and v_i is the thermal velocity of the ions. Eq. (9) implies that the fluctuation-induced transport occurs at such a high rate that the particle flux on the electrode surface is its maximum possible value, the kinetic theory value $\phi = n_s v_i/4$. If each of N identical electrodes surrounding the plasma has associated with it a sheath of area A_s, then $A = NA_s$ and the particle confinement time associated with the electrodes can be obtained by combining eqs. (8) and (9),

$$\tau_p = \frac{4\bar{n}_e V_P}{n_s v_i A} = \frac{4\bar{n}_e V_P}{N n_s v_i A_s} = \frac{\tau_0}{N}, \tag{10}$$

where τ_0 is the particle confinement time resulting from a single electrode.

If a toroidal plasma has a mean minor radius a and a major radius R, the toroidal volume is

$$V_P = 2\pi^2 a^2 R. \tag{11}$$

If an electrode encircles the plasma minor circumference and if the sheath has a diameter d_s, the sheath area is

$$A_s = 2\pi^2 a d_s. \tag{12}$$

Substituting these two expressions into eq. (10) yields

$$\tau_p = \frac{4\bar{n}_e a R}{N n_s v_i d_s} = \frac{\tau_0}{N}. \tag{13}$$

When all other factors are held constant, the particle confinement time is inversely proportional to the sheath minor diameter.

The scaling implied by eq. (13) states that if the particle confinement can be optimized so that parasitic ion currents are negligible and the dominant ion loss is through the electrode sheaths, the particle confinement time will be inversely proportional to the number of identical electrodes. It also follows from eq. (10) that the particle confinement time resulting from the irreducible minimum of one electrode required to bias the plasma is proportional to plasma volume and inversely proportional to the area of the sheath separating the electrode from the plasma. The particle confinement time does not depend on the electron kinetic temperature, the electrode voltage, or the magnetic field.

The scaling given by eq. (13) is that resulting from an non-ambipolar flow of ions to a negatively biased electrode in contact with a toroidal plasma. The electrode acts like a large Langmuir probe in ion saturation, or a "biased limiter" in contact with the plasma. Such formation of a negative toroidal electrostatic potential well for ions has been deliberately accomplished in the EFBT plasma, and apparently has resulted in improved confinement on at least one tokamak plasma [24–26], where improved ion heating, confinement times, and number densities were observed.

The scaling law of eq. (13) bears a remarkable resemblance to the phenomenological Alcator scaling. If the sheath number density n_s is independent of the plasma operating conditions, the particle containment time would be linearly proportional to the electron number density, as is characteristic of Alcator scaling. Like Alcator scaling, the particle containment time of eq. (13) is independent of magnetic field, directly proportional to the plasma electron number density, and is proportional to the product of the major and minor radii. Since Alcator experiments are generally performed with the same aspect ratio from one experiment to the next, the products of major and minor radii could not be experimentally distinguished, thus far, from a dependence on the square of the plasma radius.

5.2. Experimental evidence for model

A series of measurements were carried out to test the confinement model implied by eqs. (10)

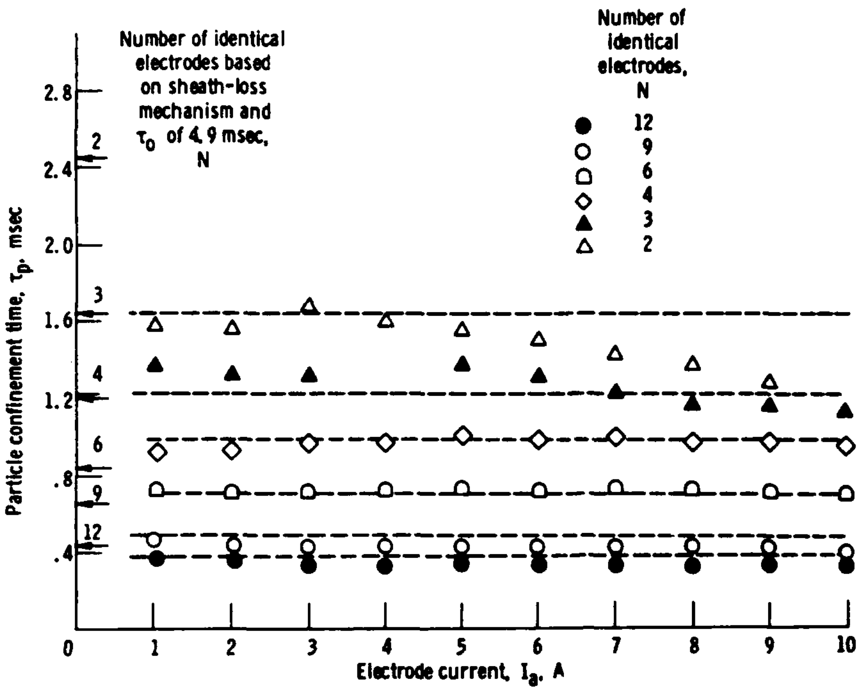


Fig. 21. Particle confinement time as function of electrode current for various numbers of identical electrodes surrounding plasma volume-run series AGY, AGZ, AHA, and AHB.

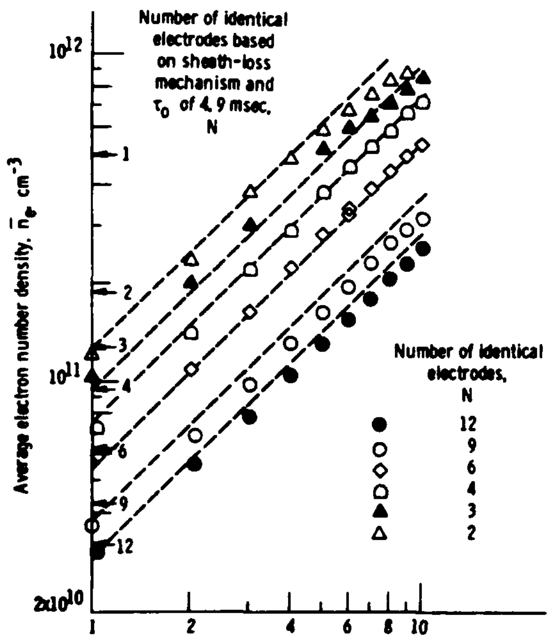


Fig. 22. Average electron number density as function of electrode current-run series AGY, AGZ, AHA, and AHB.

and (13). These consisted of measurements of the average electron number density as a function of the electrode current, for several combinations of negatively biased electrodes. Figs. 21 and 22 show the particle confinement time and average electron number density as functions of electrode current for symmetric arrangements of 12, 9, 6, 4, 3, and 2 electrodes, respectively. The arrows on the ordinates in figs. 21 and 22 were drawn on the assumptions that sheath losses are the sole particle-loss mechanism and that a particle confinement time τ_0 of 4.9 ms would result if the plasma could be generated with a single electrode. As is evident, the experimental data lie somewhat below the arrows, suggesting that an additional, "intrinsic" loss process occurs in this plasma. The dashed lines in figs. 21 and 22 are based on the particle confinement time given by eq. (13), with N denoting the appropriate number of electrode rings, but otherwise incorporating this parasitic loss. The best-fitting intrinsic confinement time for one set of data was 5.0 ms, and under more nearly optimized operating conditions, the intrinsic confine-

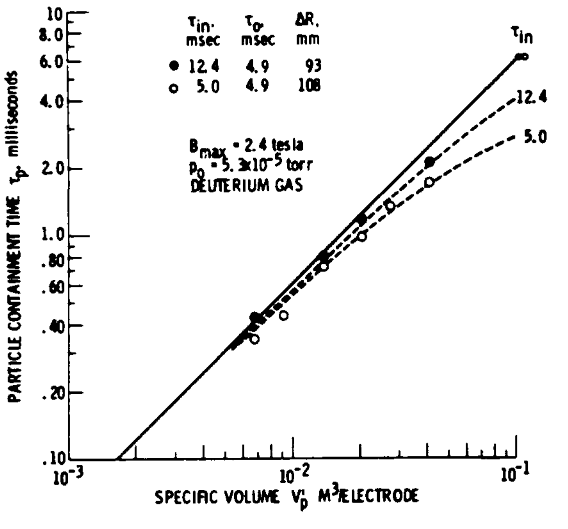


Fig. 23. Particle confinement time as function of specific plasma volume-run series AGY, AGZ, AHA, AHB, AGU, AGV, and AGW. Single-electrode confinement time, τ_0, 5.0 ms.

ment time was 12.4 ms for parasitic losses to this virtual electrode.

The data of fig. 23 tend to confirm the volume scaling predicted by eq. (13). This equation states that if intrinsic losses are negligible, the particle confinement time will be proportional to the specific volume (i.e., the volume of plasma per electrode). The radial profiles of number density did not change as the number of electrodes was changed, so the ratio $\bar{n}_e/n_s$ in eq. (13) should remain constant. The sheath area per electrode A_s and the ion kinetic temperature are known from previous work (refs. 34 and 46) not to depend on the number of electrodes. The solid line in fig. 23 is the predicted particle confinement time for no parasitic losses, a single electrode, and a single-electrode particle confinement time τ_0 of 4.9 ms. The open data points in fig. 23 are the same data plotted in figs. 21 and 22, with 2, 3, 4, 6, 9, and 12 electrodes and an intrinsic confinement time τ_{in}, due to parasitic losses on a virtual electrode, of 5.0 ms. The solid data points represent nearly optimum confinement (τ_{in} of 12.4 ms) with 2, 4, 6, and 12 electrodes. τ_{in} would be infinite if there were no virtual electrode to collect parasitic losses. The dashed lines represent the particle confinement times τ_p predicted by eq. (13) for a τ_0 of 4.9 ms and the values of τ_{in} and major radius [40] shown in the key. The particle confinement time scales with the plasma volume per electrode as predicted by eq. (13), with the departures of the experimental data from a 45° direct proportionality being consistent with parasitic losses unrelated to processes in the electrode sheath.

A further test of the scaling law of eq. (13) can be made by varying the electrode cross-section. Fig. 24 shows the particle confinement time as a function of the plasma electron number density for single electrodes with two different cross-sections. The data represented by the open circles were taken with the tungsten-wire electrode (fig. 3c), and the data represented by the open squares were taken with the dual, stainless-steel tube electrode (fig. 3b). From visual observations the sheaths appeared to have a radial thickness, independent of operating conditions and electrode minor diameter, of about 6 mm. The smaller diameter, tungsten-wire electrode given particle confinement times about 1.7 times longer than those

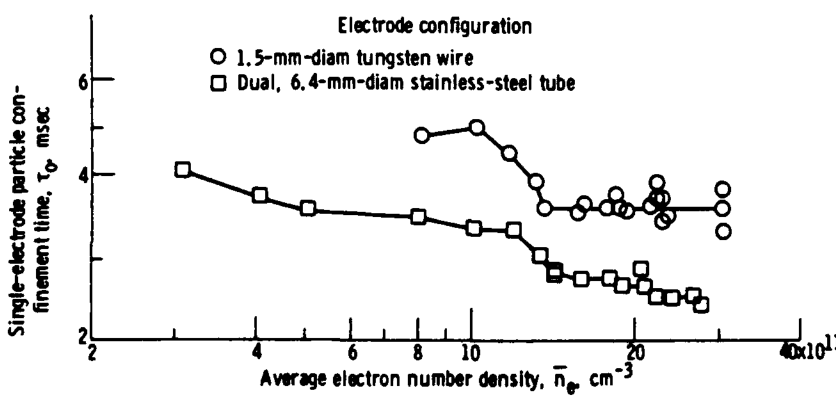


Fig. 24. Particle confinement time as function of average electron number density for two electrode configurations-run series AJL and AJJ.

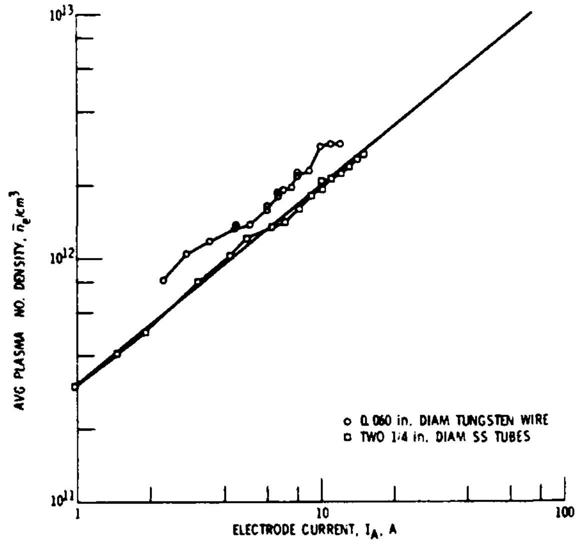


Fig. 25. Average electron number density as function of electrode current for two electrode configurations-run series AJL and AJJ.

of the stainless-steel electrode, as is consistent with the functional dependence predicted by eq. (13).

Fig. 25 also shows the enhancement of plasma density, at a given electrode current, that results from the improved confinement of a smaller diameter electrode.

Finally, eq. (13) predicts that the particle confinement time is independent of magnetic field. This has been confirmed in ref. 33, where, under poorly optimized operating conditions, it was shown that the confinement time was approximately independent of magnetic field over a factor of 10 variation in the magnetic field strength. These data are replotted in fig. 26. The data are consistent with a particle confinement time independent of magnetic field strength and are inconsistent with Bohm or classical scaling, where the functional dependence on magnetic field would be proportional to B or B^2, respectively.

6. RF plasma emission

6.1. Electron plasma frequency emissions

The NASA-Lewis EFBT plasma produced electrostatic potential fluctuations and near-field rf emissions over a wide range of frequencies, from a few kHz to several GHz. A typical detection

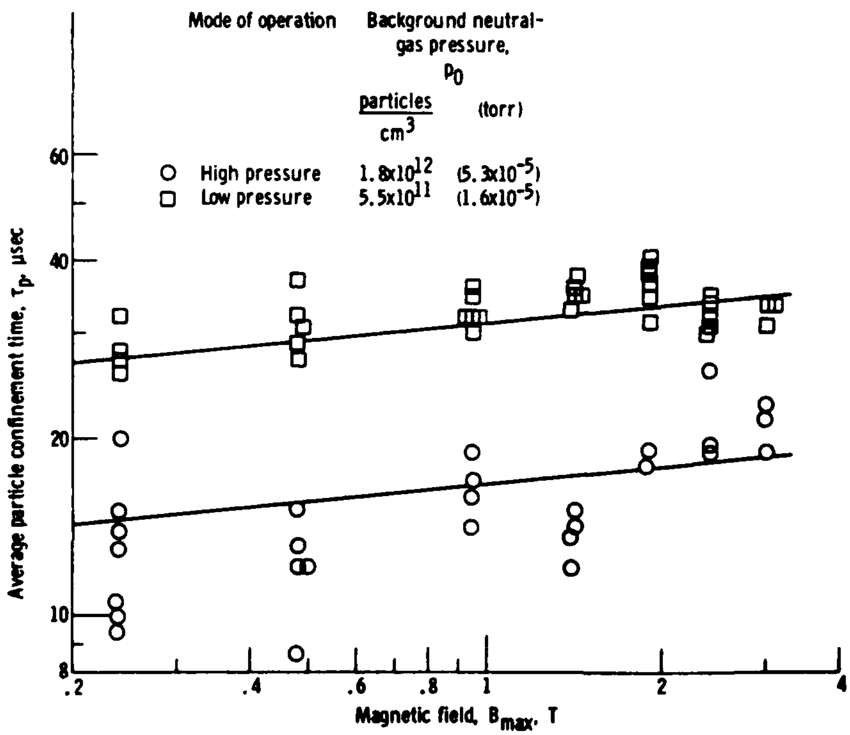


Fig. 26. Particle confinement time as function of magnetic field strength, for off-optimum operating conditions.

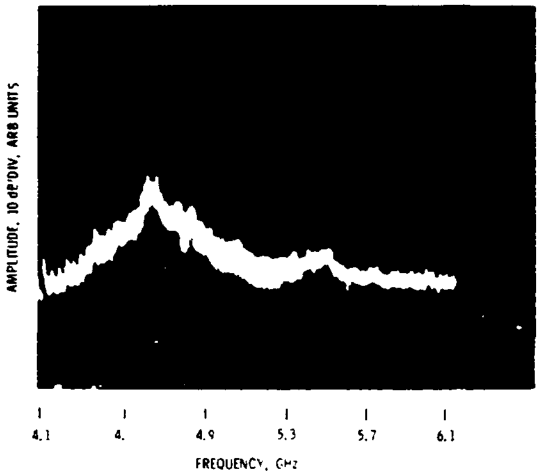


Fig. 27. Typical spectrum of broad amplitude emission peak near the electron plasma frequency as observed on the spectrum analyzer. Emission peak frequency, 4.62 GHz. Horizontal scale, 200 MHz per division.

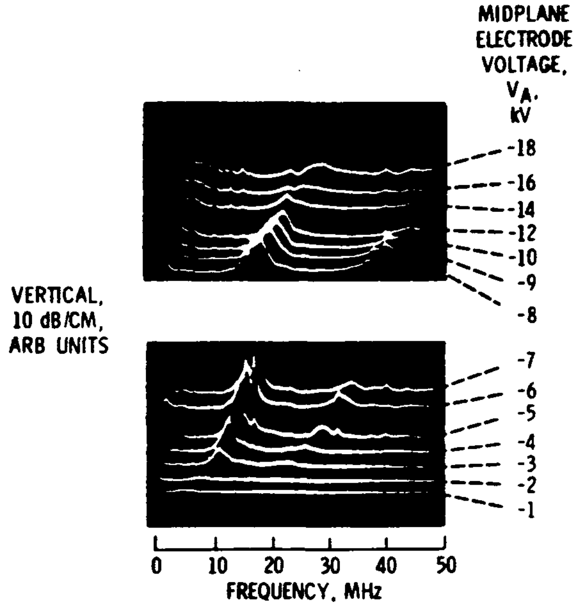


Fig. 28. Rf emission in the vicinity of the lower hybrid frequency, as a function of midplane electrode voltage.

system consisted of a capacitive probe or a coaxial waveguide antenna inserted in a quartz reentrent tube within a few centimeters of the visible boundary of the plasma. These antennae were connected to spectrum analyzers which displayed the frequency band of interest.

The electron plasma frequency was observed at frequencies that characteristically were several GHz. An example is shown in fig. 27, in which the peak of the electron plasma frequency is visible at about 4.4 Ghz. This peak frequency was observed to be independent of magnetic field, and to have the expected square root dependence on electron number density [47]. The observed frequency corresponded to an emitting region in the outer, low density regions of the plasma near the visible boundary, or perhaps from the electrode sheaths. The broad frequency peak illustrated in fig. 27 was typical of emissions at the electron plasma frequency.

6.2. Lower hybrid frequency emissions

Under suitable conditions of operation, emission peaks were observed on the spectrum analyzer at frequencies consistent with the lower hybrid frequency [34]. These frequencies were observed from about 10 to 40 MHz, and a characteristic example is shown in fig. 28. The electrode voltage and electron number density increased from the bottom to the top of this figure, and the intensity and frequency of the emission changed correspondingly. The magnitude and functional dependence of this emission peak on electron number density and magnetic field are consistent with the lower hybrid frequency [34].

6.3. The geometric mean emission frequency

During experiments on the NASA-Lewis EFBT experiment, very clear emissions were observed at a frequency which is inconsistent with familiar mechanisms of plasma emission. The detection system consisted of a 1.5 m long, 50 Ω miniature coaxial line, one end of which was a straight wire antenna. The other end of the coaxial line leads to a spectrum analyzer capable of scanning the range from 10 MHz to 18 GHz.

In fig. 29 is shown the emission spectra from 0 to 100 MHz at three distances of the antenna from the plasma boundary. The peak at 65 MHz is the new mode of emission. The radiation appeared as a narrow peak that shifted in frequency as the plasma parameters were varied.

The emission was found to increase in frequency as the plasma density was increased from $5 \times 10^9/\mathrm{cm}^3$ to $2 \times 10^{11}/\mathrm{cm}^3$. The experimental data are shown in fig. 30a, in which the observed emis-

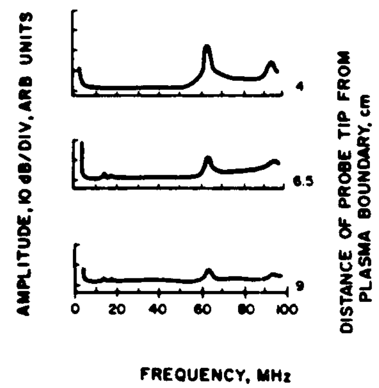


Fig. 29. Rf emission at the geometric mean plasma frequency at 65 MHz as a function of the distance of the probe tip from the plasma boundary.

sion frequency is plotted against the average electron number density measured with a microwave interferometer. For these conditions, the toroidal magnetic field under the mirror coils was B_{max} = 2.4 T, and the background gas pressure was 7.4 × 10^{-5} Torr of deuterium The emission frequency

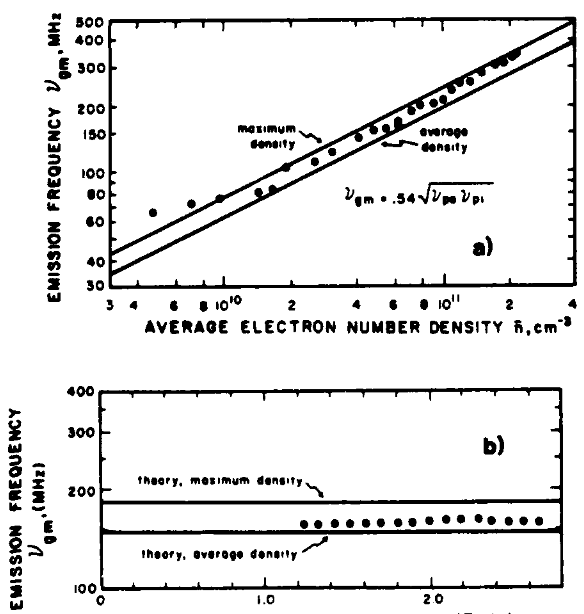


Fig. 30. (a) The observed emission frequency as a function of the average electron number density. (b) The observed emission frequency as a function of the maximum magnetic field. The average electron number density was held constant at 5.8 × 10^{10}/cm^3, and the background deuterium density was 2.6 × 10^{12}/cm^3. The emission frequency plotted is $\nu_{gm} = 0.54\,(\nu_{pe}\nu_{pi})^{1/2}$.

was observed to have a square root dependence on electron number density (the straight lines have a slope of 1/2), but its absolute magnitude was far too low to be consistent with the electron plasma frequency, and far too high to be consistent with the ion plasma (or lower hybrid) frequency. It was found that the best-fitting straight line through the data of fig. 30a had the empirical form

$$\omega = 0.64\,(\omega_{pe}\omega_{pi})^{1/2}. \tag{14}$$

To determine whether this emission was related to a hybrid or cyclotron frequency, the plasma density was kept constant at $n_e = 5.8 \times 10^{10}$/cm^3, while the magnetic field was varied. The results, over more than a factor of 2 in magnetic field, are shown in fig. 30b. These data are consistent with no dependence upon magnetic field strength.

In interpreting these results, it was assumed [41,42] that this bumpy-toroidal plasma acts like a toroidal array of Penning discharges end-to-end with equal and interpenetrating beams of electrons acting on a background of plasma ions. The dispersion relation appropriate for this situation is [41,42]

$$D(\omega) \equiv \frac{\frac{1}{2}\omega_{pe}^2}{(\omega - kv)^2} + \frac{\frac{1}{2}\omega_{pe}^2}{(\omega + kv)^2} + \frac{\omega_{pi}^2}{\omega^2} = 1. \tag{15}$$

Solution via successive approximations yields, for the most rapidly growing and decaying modes [41,42],

$$k^2v^2 = \omega_{pe}^2,$$

$$\omega = \pm\frac{(\omega_{pe}\omega_{pi})^{1/2}}{\sqrt{2}\sqrt[4]{3}} \pm \frac{\mathrm{i}(\omega_{pe}\omega_{pi})^{1/2}}{\sqrt{2}\sqrt[4]{3}}. \tag{16}$$

The real part of the frequency is given by

$$\omega_r = \frac{(\omega_{pe}\omega_{pi})^{1/2}}{\sqrt{2}\sqrt[4]{3}} = 0.537\,(\omega_{pe}\omega_{pi})^{1/2}. \tag{17}$$

The agreement of the geometric mean frequency, given by the growing solution of eq. (16), with the experimental observations is indicated by the straight lines in figs. 30a and 30b. The lower line is the relation predicted by eq. (17) for the chord-averaged electron number density from a microwave interferometer, which is plotted on the abscissa; the upper straight line is predicted by eq. (17) for the maximum number density on the

plasma axis, with the assumption of a parabolic radial density distribution. The points outside these lines at low number density are the result of a systematic error occasioned by measuring these low densities. The agreement between theory and experiment is very good. Over a factor of more than 2 in magnetic field, and more than 40 in density, the predicted frequency has both the proper functional and quantitative dependence. This instability, perhaps in modified form, probably will be characteristic of all Penning-discharge-like plasmas in which interpenetrating beams of "pigging" electrons are found.

7. Plasma–electrode interaction issues

It is fundamental to the magnetoelectric confinement approach that the confined plasma be biased to high positive or negative potentials by an electrode connected to an external power supply. In spite of the long familiarity with limiters and divertors in tokamak research, the presence of biasing electrodes in or near the confined plasma raises several concerns. These concerns include impurity introduction into the plasma; whether the power flux to the electrodes can be handled for conditions of fusion interest; and erosion of the negative electrodes due to energetic ion bombardment. In the material below, we will summarize work reported elsewhere [48] to show that these concerns are not as limiting as one might suppose.

7.1. Impurity introduction into plasma

At first glance, it might seem that the presence of a biasing electrode in or around a plasma would introduce an unacceptable level of impurities into the plasma. To investigate this, we can make some relatively conservative assumptions, and show that these assumptions lead to acceptable impurity levels. We make the pessimistic assumption that the impurities are confined for as long as the fuel species in the plasma. This is conservative, since the larger gyroradii of the heavy impurity ions will lead to more rapid transport out of the plasma, or direct scrape-off of these large gyroradius ions on surrounding structures. If the impurity and fuel ions have the same containment times, then the largest possible concentration of impurities, in a plasma in which the impurities arise from sputtering of the negative electrode by the fuel ions, will be equal to the sputtering yield of the impurity atoms by the energetic ions. Here we also make the further conservative assumption that all neutral impurity atoms knocked off the electrode surface will be ionized and trapped in the containment volume. The sputtering yield is a function of the incoming ion energy. If we further assume that the incoming ions are of an energy corresponding to the maximum sputtering yield of the electrode material, one can then achieve impurity concentrations that would be no higher than the maximum sputtering yield of 10^{-3} for tungsten, or 0.01 for molybdenum. It is to be emphasized that these are maximum impurity concentrations. These concentrations may be less, perhaps much less, if the impurity containment times are shorter than the plasma fuel ion containment times; if the sputtered neutral atoms do not all find their way as ions into the containment volume; or if the fuel ions impinge on the electrode surface with an energy other than that corresponding to maximum sputtering yield.

7.2. Power flux to electrodes

To estimate the maximum plasma number densities and kinetic temperatures which can be maintained with biasing electrodes, we need to estimate the fluxes which can be achieved without exceeding heat transfer limitations through walls of watercooled tubing. In the aerospace field, sophisticated heat transfer techniques can be employed to remove between 1 and 5 kW/cm^2. These values will be adopted as an upper limit on heat transfer to electrodes used for magnetoelectric confinement, and this flux in turn will determine the combination of plasma number densities, ion kinetic temperatures, and flux rates which are possible.

In ref. 48 it has been shown that the relationship between the power flux on a surface, and the ion number density and kinetic temperature immediately above that surface is

$$P_w = e n_i T_i^{3/2} \sqrt{\frac{2e}{\pi m_i}} \quad [\mathrm{W/m^2}], \tag{18}$$

where T_i is the ion kinetic temperature expressed in eV, and m_i is the ion mass.

Eq. (18) allows us to determine the combination of ion number density and ion kinetic temperature

which will result in a given power flux to the electrode surfaces. This combination of ion number density and ion kinetic temperature is shown in fig. 31 for power fluxes of 1 kW/cm^2, a large but manageable heat flux to the surface of water cooled tubing, and 5 kW/cm^2, which represents the approximate upper limit possible with water cooled tubing, even by sophisticated heat transfer techniques. In order not to exceed these power loadings on the wall, one must operate at or below the lines shown.

It is clear that the ion number density or the ion kinetic temperature can separately attain values characteristic of the interior of fusion grade plasmas, but one cannot simultaneously obtain such densities and temperatures.

The results presented in fig. 31 would be pessimistic, if one had no alternative but to achieve magnetoelectric confinement with electrodes going through the minor diameter of the plasma; however the results achieved with electrodes such as that shown in fig. 3a, and by the work on biased limiters on tokamaks [24–26] indicate that a toroidal plasma may be biased with electrodes which surround the minor circumference of the plasma. These electrodes are in a substantially lower portion of the density profile than that on the plasma axis, and so it might not be out of the question to bias a fusion grade plasma, if that were necessary, while not exceeding the conditions implied in fig. 31.

7.3. Electrode erosion

The principal effects anticipated from surface bombardment by ions are sputtering and erosion.

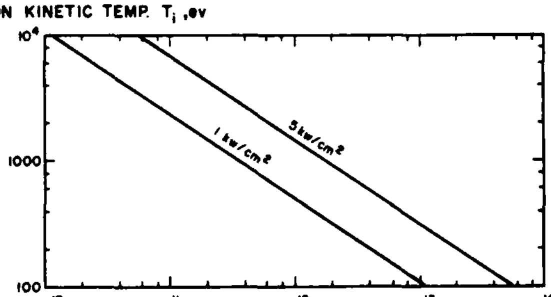


Fig. 31. Relation between the ion kinetic temperature and the ion number density which results in a power flux to the electrode surface of 1.0 and 5.0 kW/cm^2.

This erosion rate can be calculated from known properties of electrode materials, and it is therefore possible to determine how long it might take to produce significant electrode erosion. In ref. 48 it has been shown that the erosion rate is given by

$$v_e = \frac{\phi_s}{N} = 100\,\epsilon n_i(\mathrm{cm}^{-3})\,\frac{eT_i}{2\pi m_i}\,\frac{A}{A_0\rho}, \tag{19}$$

where the erosion velocity is in cm/s, ϵ is the sputtering yield in atoms per incident ion, A_0 is Avogadro's number, 6.02×10^{23} atoms/ g · atom, ρ is the density of the material in grams per cm^3, A is the atomic mass number of the wall material, and n_i is the number density of the plasma immediately above the electrode surface in ions/cm^3.

The time required to erode a thickness of material L is given by

$$T = \frac{L}{3600\,V_e}\ [\mathrm{h}]. \tag{20}$$

We can calculate a maximum possible erosion rate by assuming that the incident ions have an energy equal to the energy at the maximum of the sputtering curve. The sputtering yield ϵ is a function of energy, and for most materials has a maximum somewhere in the energy range of fusion interest, between one and 50 keV. We therefore assume that all of the incoming ions have a kinetic temperature T_i corresponding to the energy at the maximum of the respective sputtering curve for each material.

Fig. 32 shows the time required to erode 1 mm

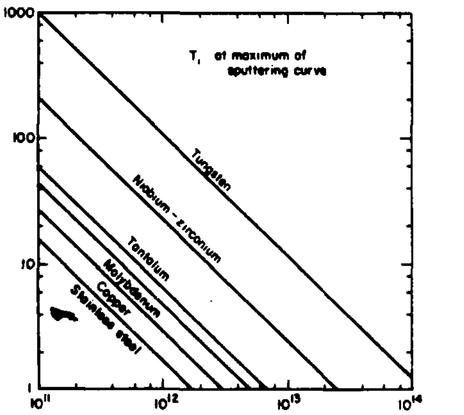


Fig. 32. Time to erode 1 mm, as a function of plasma number density, for candidate electrode materials.

of material for the various metals shown, as a function of the ion number density above the plasma surface [48]. Since these represent the maximum possible erosion rates, it is clear that exposure times of many hours will be required to exhibit significant erosion in a fusion reactor context. These erosion rates are slow enough that the biasing electrodes required for magnetoelectric confinement can be moved continuously through the plasma at a slow rate, or replaced, long before erosion would threaten the structural integrity of the cooling passages.

8. Discussion

8.1. Absence of MHD instabilities

Plasmas that are confined only by static magnetic fields are subject to a variety of magnetohydrodynamic (MHD) instabilities, which arise from reservoirs of free energy in the confined plasma. In the ELMO bumpy-torus configuration, low-frequency, long-wavelength MHD instabilities pose the greatest threat to confinement [49,50]. The most severe of these are driven by centrifugal forces associated with motion of the particles along the curved magnetic field lines in the midplanes where the field lines bow outward, and also by the centrifugal forces associated with the drift of particles about the magnetic axis. In the ELMO experiment, MHD modes are stabilized by the perturbed magnetic field resulting from relativistic, high-beta electron rings that are trapped in the midplane of each sector.

The radial electric fields characteristic of the NASA-Lewis bumpy-torus experiment exert forces on individual particles that dominate the relatively weak centrifugal or "gravitational" forces responsible for the usual MHD instabilities. The ratio of the electric field to the centrifugal forces is

$$\gamma = \frac{a_c E_r e}{m v^2} = \frac{a_c E_r}{4 T_i'}, \tag{21}$$

where E_r is the radial electric field in V/m, a_c is the radius of curvature of the field line, and T_i' is the ion kinetic temperature in eV.

Fig. 33 shows the combinations of ion kinetic temperature and radial electric fields that result in equality between the electric field and centrifugal forces for the bumpy-torus plasma. The Lewis EFBT experiment operated in the shaded region, for which the electric field forces dominated the weak centrifugal forces that drive the MHD instabilities. For this reason, MHD instabilities should not arise. The experimental observations reported herein are consistent with this expectation. If such instabilities were present, they would appear as a prominent, coherent peak in the potential and/or density fluctuation spectra, such as those in fig. 12. Under many operating conditions, however, the fluctuation spectra are quite turbulent, and no such prominent peaks are evident. The peaks that were observed are due to E/B drift and the rotating spokes that resulted from the diocotron instability. The absence of low-frequency MHD instabilities in this plasma is also consistent with the requirements of the Bohr-Van Leeuwen theorem [17], which states that a state of kinetic equilibrium can be achieved if the internal reservoirs of free energy are minimized. The turbulent nature of the fluctuations and their Gaussian amplitude statistics therefore are consistent with the absence of MHD instabilities.

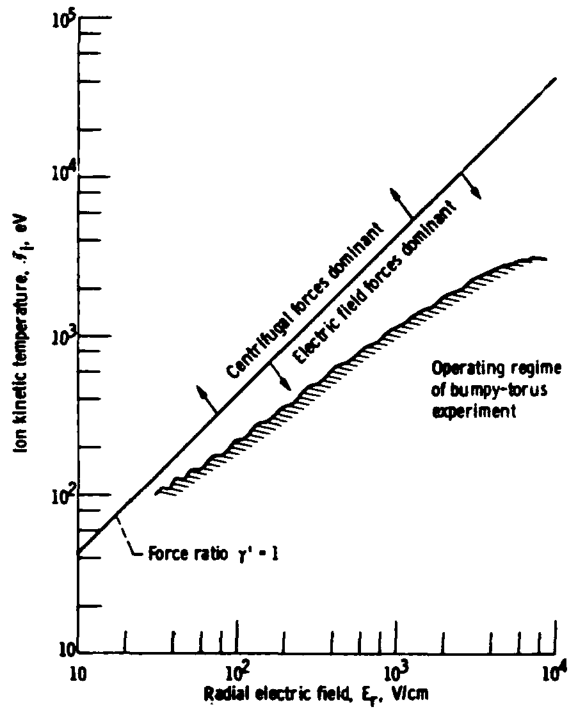


Fig. 33. Ion kinetic temperature as function of radial electric field.

8.2. Radial electric fields

The profiles of floating potential presented in figs. 4 and 5 reveal radial electric fields in excess of 1000 V/cm. The electric fields increased with increasing radial penetration, at least halfway to the axis of the plasma. The magnitude and radial extent of these electric fields was far greater than could be explained by simple Debye length considerations; it was also greater than would be expected on the basis of ambipolar phenomena.

8.3. Parametric variations

The effects of the various electrode shapes and configurations that were investigated are consistent with the scaling law of eq. (13). When the weak, vertical magnetic field was optimized, the number density and particle confinement times improved as the number of identical electrodes was reduced, as is consistent with the data in figs 21 and 22. The data in figs. 6, 7, 16 and 17, and 25 indicate not only that negative polarity on the electrodes confines particles much better than positive polarity, but also that a tubular water-cooled electrode passing across the minor diameter of the plasma results in slightly higher densities and confinement times than the D-shaped electrode shown in fig. 3a.

Consistent with the scaling law of eq. (13), smaller diameter electrodes resulted in higher number densities and longer particle confinement times than did larger diameter electrodes. The relevant diameter appearing in eq. (13) is apparently the diameter of the sheath and not that of the electrode itself. Particle confinement times of 6 ms and average electron number densities of 3.2×10^{12} particles per cm^3 were achieved with an electrode consisting of a single 1.5 mm diameter tungsten wire across the minor diameter of the plasma (fig. 25). This small-diameter electrode had to be cooled by radiation but was not hot enough to be electron emitting.

8.4. Implications of confinement time scaling

The confinement scaling law of eq. (13) describes the functional dependence of the particle confinement time in this plasma. The processes underlying this model are fundamentally different from those that exist in pure magnetic confinement devices. The latter are restricted to outward transport of the plasma only, at rates determined by some modification of classical diffusion. The use of strong inward-pointing radial electric fields in magnetoelectric confinement admits the possibility of radially inward particle transport, against the density gradient over much of the plasma surface, by fluctuation-induced transport. The strong electric fields that were externally imposed on this plasma were generally much higher than those to be expected from ambipolar phenomena.

The experimental data in figs. 21 and 22 are consistent with the assumption that all other ion loss processes have been minimized and that the dominant loss process in this plasma is withdrawal of ions by the negatively biased electrodes. The particle confinement time decreased as more electrodes were applied to withdraw ions from the plasma. The strong dependence of plasma density and particle confinement time on the number of identical electrodes used to bias the plasma demonstrated that confinement was dominated by physical processes associated with the individual electrodes rather than by processes that took place between the plasma and the surrounding grounded walls. The various forms of classical diffusion would be an example of the latter processes. The electron loss processes in the region between the plasma and the wall were controlled by the ion losses to the electrode in such a way that the ion and electron losses from the plasma volume were in detailed balance in the steady state.

9. Conclusions

The toroidal plasma studied in this series of investigations is subject to intense, turbulent, fluctuating electric fields superimposed on dc, radial electric fields. The turbulent plasma rotated about the plasma axis with a velocity appropriate to the local E/B drift velocity. This drift velocity reversed direction when the sign of the electric field was reversed. Under operating conditions that produced the highest densities and particle confinement times, the plasma was turbulent, with no coherent peaks in the spectrum of either the density or the potential fluctuations. Under other conditions, discrete rotating spokes, probably a manifestation of the diocotron instability, were superimposed on the background turbulent spec-

tra and rose from 10 to 20 dB above it.

The amplitude statistics of both the density and the potential fluctuations were found to be Gaussian for the most part, with near-zero skewness and a kurtosis (fourth moment) of about 3.0. The spectral index of the density and potential fluctuations ranged from 2 to 6 and did not cluster near the theoretically expected value of 5.0, regardless of whether the dispersion relation relating radian frequency and wave number was linear or not.

The radial profiles of floating potential revealed that electric fields, sometimes in excess of 1000 V/cm during these experiments, penetrated at least halfway to the axis of the plasma; that the electric field pointed inward when the plasma was negatively biased; and that the electric field pointed outward when the plasma was positively biased. The radial profiles of transport rate indicate that when the weak vertical magnetic field was properly optimized, the transport of ions was in the direction of the electric field and tended to increase as the probe was moved inward toward the plasma axis.

When the operating conditions were properly optimized, the particle confinement time was virtually independent of the plasma number density. Positive electrode polarity confined the plasma much less well than negative polarity, for which the electric field pointed radially inward. Particle number densities and confinement times were at least 5 times greater when the electric field pointed inward and resulted in radially inward ion transport.

A water-cooled electrode consisting of a vertical, stainless-steel tube through the minor diameter of the plasma resulted in longer confinement times and higher number densities than a standard D-shaped electrode surrounding the minor circumference of the plasma. In addition, the particle confinement time tended to decrease with increasing number density for the standard D-shaped electrode but was nearly independent of number density for the vertical stainless-steel tube electrode.

It has been shown that the magnitude of the ion flux, when multiplied by the plasma surface area, differed by less than a factor of 2 from the current drawn by the power supply. Therefore the radial flux of particles is probably relatively uniform over the entire plasma surface, and the probes sampled a typical position insofar as the radial transport rate is concerned. The fact that the electrode current was directly proportional to the observed particle flux over nearly a factor of 100 in these quantities suggest that the fluctuation-induced radial transport mechanism dominated the transport process in this plasma.

The radial transport has been shown to depend critically on the value of a weak, vertical magnetic field applied to the confinement volume. The field must be optimized in order to assure the best possible confinement. Extreme values of this vertical magnetic field can reverse the direction of radial particle transport.

A simple model of particle confinement has been proposed in which the particle confinement time is independent of magnetic field; directly proportional to the plasma volume and average electron number density; and inversely proportional to the surface area of the sheath surrounding the electrode, to the ion thermal velocity, and to the electron number density at the outer surface of the electrode sheath. Direct experimental evidence has confirmed these functional dependences (except that on ion velocity, which was not measured) and has also confirmed that the particle confinement time was approximately independent of the magnetic field. It has been shown that confinement is determined by physical processes associated with the individual electrodes or their sheaths and not by transport processes occurring between the plasma and the surrounding grounded walls. This scaling law for particle confinement time, if extrapolated to the fusion reactor regime, predicts fusion reactors considerably smaller in volume than would be the case if the plasma transport were controlled by classical diffusional processes. The radial transport processes in this plasma are not diffusional in nature, and radially inward transport of ions against a density gradient has been observed.

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CORRELATION OF RF EMISSION, PLASMA WAVE PROPAGATION, AND PLASMA TURBULENCE IN CLASSICAL AND MODIFIED PENNING DISCHARGES

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Abstract

We have taken data from two versions of the Penning discharge which contain highly turbulent, electric field dominated plasma with densities up to $3 \times 10^{10}/cm^3$. Auto and cross-correlation techniques were used to obtain information about the turbulence and wave propagation in this plasma from capacitive probe and microwave scattering signals.

1. Introduction

We have performed a paired comparison experiment on steady state plasma created in classical [1] and modified Penning discharges [2] in uniform and magnetic mirror geometries, respectively. Our classical Penning discharge consists of a uniform magnetic field up to 0.40 Tesla, and our modified Penning discharge of a 5.7:1 magnetic mirror ratio with a maximum magnetic field on the axis up to 0.40 Tesla. The electrons are trapped in an axial electrostatic potential well, and in both cases form a plasma about 10 cm in diameter in the midplane. The electron population forms two interpenetrating beams in the background plasma which give rise to the geometric mean and other plasma instabilities [3,4]. These plasmas support high levels of electrostatic turbulence, axial electric fields up to several hundred volts per centimeter, and emit broadband electromagnetic radiation over the frequency range from below 1 MHz to more than 2 GHz [4,5,6]. These plasmas draw anode currents up to 0.5 amps at up to 7.0 kV anode potential, and characteristically have densities that range from below $10^8/cm^3$ to above 5×10^{10}. Characteristic electron kinetic temperatures observed with Langmuir probes range from 5 to 300 eV.

Data have been taken from both discharges with an analog-to-digital data handling system which allows us to analyze the digital time series

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generated by electrostatic potential fluctuations detected by capacitive probes at two azimuthal or axial positions in the plasma. Auto- and cross-power spectra, the phase coherence spectrum, and dispersion relations have been observed for both plasmas. Rotating spokes, driven by E/B drift, and propagating waves have been observed and their dispersion relations obtained. These electrostatic potential fluctuations have been compared and correlated with microwave scattering results from the classical Penning discharge plasma.

RF emissions over the frequency range from 100 to 1400 MHz have been measured in the far radiation field with a spectrum analyzer connected to a specially calibrated broadband conical spiral antenna. The plasmas emit radiation with numerous harmonics of a fundamental frequency over a broad frequency range up to at least 2 GHz [4,5,6]. We have also used our antenna to make local power flux and net radiated power measurements. Axial ion energy distribution functions were measured with a retarding potential energy analyzer in both discharges, and varied from monoenergetic to Maxwellian with characteristic energies from below 100 eV to several keV. High levels of electrostatic turbulence resulted in more nearly Maxwellianized energy distributions. The modified Penning discharge seemed to produce more nearly Maxwellianized distribution functions than the classical Penning discharge, with its flat axial magnetic field profile. In both discharges, profiles of plasma potential and electron number density and kinetic temperature were taken along the axis of symmetry with a Langmuir probe under a variety of operating conditions.

2. The Modified Penning Discharge

With helium gas at pressures above 2×10^{-4} Torr, the axial profile of electrostatic potential was quite flat, with axial electric fields of only a few volts per centimeter at most. Below 10^{-4} Torr, however, electric fields up to 100 volts/cm were observed. On Fig. 1a is an example of a monotone decreasing axial potential profile for a gas pressure of 4×10^{-5} Torr of helium, B_{max} = 0.15 Tesla, anode voltage V_a = 4700 volts, a maximum number density on the midplane of $1.2 \times 10^8/cm^3$, and a characteristic T_e = 60 eV. On Fig. 1b is an interesting example not only of strong axial electric fields, but of an axial electrostatic potential well for ions, about 600-800 eV deep. The helium gas pressure and magnetic field were approximately twice that of Fig. 1a; $T_e \simeq 300$ eV, and other parameters were approximately the

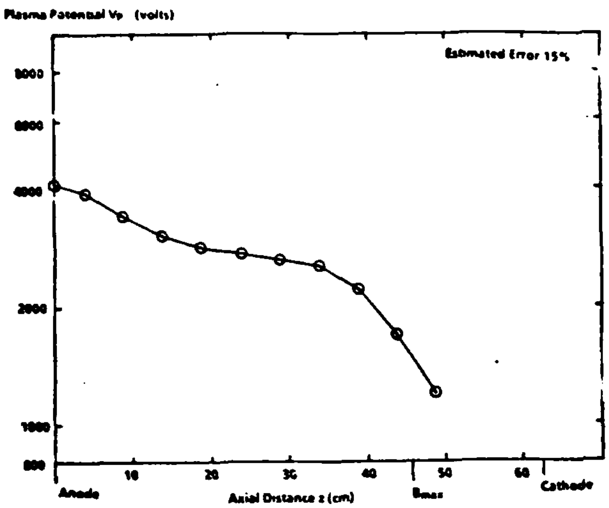

Figure 1A
Axial Profile of Plasma Potential P_0 = 4 x 10[illegible] torr , He gas
B_{max} = 1.5 kilogauss , V_{anode} = 4700 volts

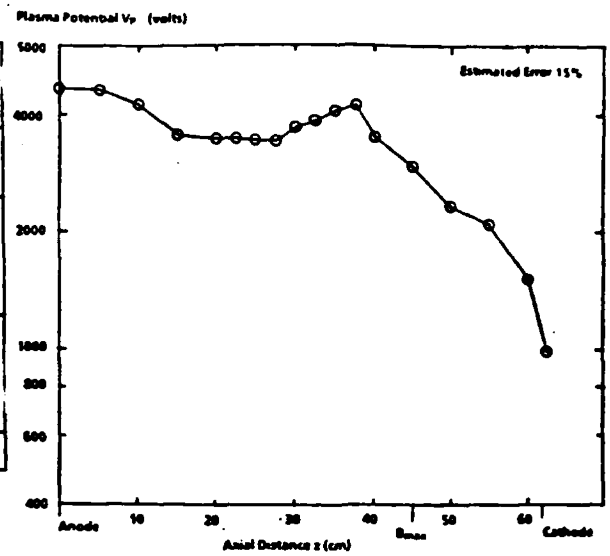

Figure 1B
Axial Profile of Plasma Potential P_0 = 8.4 x 10[illegible] torr , He gas
B_{max} = 3.0 kilogauss , V_{anode} = [illegible] volts

same. Both plasmas were highly turbulent, and the energy of ions escaping to the cathodes (measured with a retarding potential energy analyzer) were on the order of kilovolts. The high axial electric fields observed imply a very high anomalous resistivity for the plasma. This plasma emits multiple harmonics of a fundamental frequency which appears to be the geometric mean emission frequency associated with the interpenetrating beam plasma instability [3]. The envelope of these harmonic peaks has a maximum which is consistent with the electron plasma frequency of this discharge.

3. The Classical Penning Discharge

The classical Penning discharge also emits broadband RF radiation and under certain circumstances, the spectrum is white-noise like from 0.6 MHz to above 1.0 GHz [4]. Significant radiation has been observed above 2.0 GHz. Harmonics of the geometric mean emission frequency are observed, with a maximum envelope amplitude near the electron plasma frequency.

Measurements from a microwave scattering apparatus consisting of a 27 GHz Gunn diode in a homodyne mixer configuration were taken. Approximately 100 milliwatts of microwave power was incident on the plasma in the ordinary mode. The scattered power is observed in a plane normal to the plasma axis for scattering angles from 20° to 160°. When the scattered signal from the crystal detector is fed into a spectrum analyzer, electron number density fluctuations from 10 to 40 kHz are observed. These appear to obey a linear dispersion relation. On Figure 2a is shown an example of the spectrum of microwave scattering signals for argon gas at a

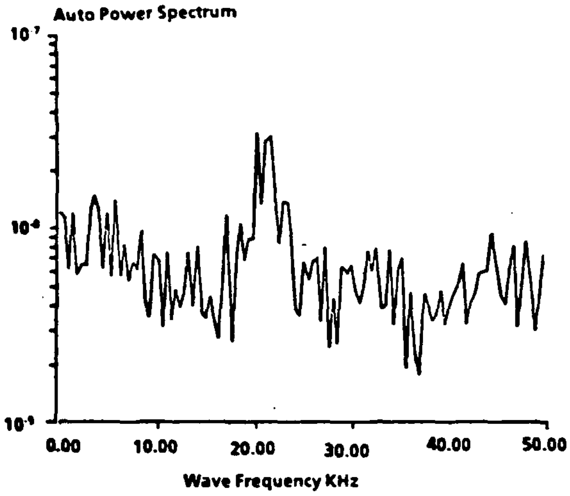

Figure 2A

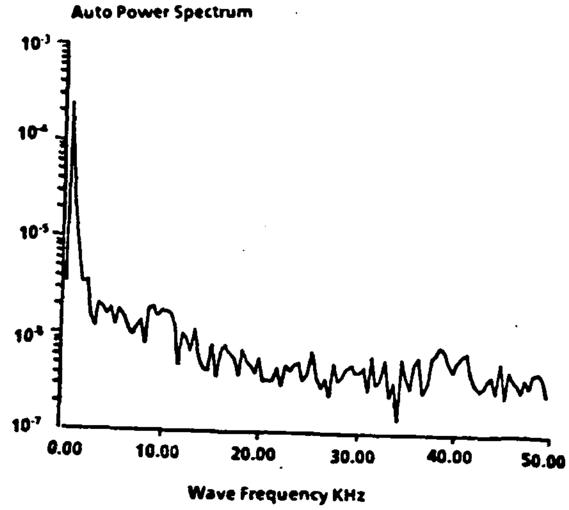

Figure 2B

pressure of 3.5 x 10^{-4} Torr, at an anode voltage of V_a = 1.8 kV, and a magnetic field of B = 0.25 Tesla. On Figure 2b is an example of the auto power spectrum taken under the same operating conditions from a capacitive probe about 3 cm outside the plasma boundary. This shows no peak in the range from 10 kHz to 50 kHz.

Acknowledgements

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DEVELOPMENT OF AN INTEGRATED DATA ACQUISITION AND HANDLING SYSTEM BASED ON DIGITAL TIME SERIES ANALYSIS FOR THE MEASUREMENT OF PLASMA FLUCTUATIONS

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ABSTRACT

The nonlinear characteristics of data obtained by many plasma diagnostic systems requires the power of modern computers for on-line data processing and reduction. The objective of this work is to develop an integrated data acquisition and handling system based on digital time series analysis techniques. These techniques make it possible to investigate the nature of plasma fluctuations and the physical processes which give rise to them. The approach is to digitize the data, and to generate various spectra by means of Fast Fourier Transforms (FFT). Of particular interest is the computer generated auto-power spectrum, cross-power spectrum, phase spectrum, and squared coherency spectrum. Software programs based on those developed by Jae. Y. Hong at the University of Texas are utilized for these spectra. The LeCroy 3500-SA signal analyzer and VAX 11/780 are used as the data handling and reduction system in this work. In this report, the software required to link these two systems will be described.

INTRODUCTION

Recent advances in electronics make it possible to use transient recorders to digitize and store high frequency transient signals. Once stored, the data is available, for transfer via various digital input/output interfaces, to computers for signal analysis, to mass storage media for archiving, and in general to any device capable of accepting digital input. The data can also be reconstructed by a digital-to-analog channel for observation on an oscilloscope. The data transferred from the transient recorders to the memory of the computer constitute a series of numbers known as a time series.

The methods of digital time series analysis are applied to the data, which includes some noise, to find the desired information. One of these methods, the Fast Fourier Transform (FFT), is used extensively in this work. Since such fiduciary data as run number, data, anode voltage and current, front panel gain settings, for each transient recorder are needed for the calculation of various spectra, this information is stored along with the raw data.

With this introduction, it is the objective of this work to develop an integrated system that allows

a) Transfer of raw data from each transient recorder, and the storage of these raw data, along with their fudiciary data, in the histogram memory of the computer.
b) Sending this information to the VAX 11/780 system.
c) Processing these data on the VAX system and returning the processed data to the LeCroy 3500SA system.
d) Plotting various spectra on the LeCroy system.

There are three different software programs all written in Fortran. The first is an interactive program which reads the raw data from the histogram memory of the computer and stores these data on a floppy disk in drive B. This program also permits the operator to enter fiduciary data about the experimental run through the keyboard. The second is a digital spectral analysis program, which was written by Jae Y. Hong.[1] This program was modified for compatibility with the other two programs written for this system. Finally, the third program reads the processed data from the VAX system and uses this data to generate plots of data on the LeCroy 3500 SA screen. This program also allows plots to be screen dumped to the LeCroy 3931A printer.

SYSTEM DESCRIPTION AND SCOPE OF WORK

The overall block diagram of the data acquisition and handling sytem is shown in Figure 1. The objective of this work is to make the LeCroy 3500 SA signal analyzer operate as a remote terminal for the VAX 11/780 system. By making the LeCroy 3500 SA two-way interactive with the VAX system, one can sample data on the LeCroy system, process the data on the VAX, and then return the data to the LeCroy for inspection and possible plotting. The work reported here falls into two categories; hardware and software. Detailed description of these two parts and individual components of this system are given below.

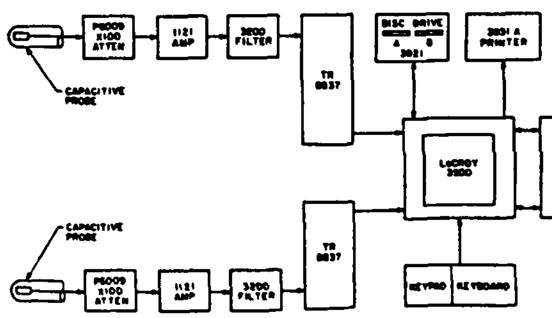

Figure 1. Block diagram of the data acquisition and handling system.

A. HARDWARE

The necessary hardware for this system is as follows.

a) Capacitive Probes:

As shown in Figure 1, two capacitive probes were used to measure potential fluctuations from which the wave number of plasma fluctuations can be obtained. These two capacitive probes are separated by a known angle at the same radius. The capacitive probes used in this system are Tektronix P6009.[2] These are low-input capacitance, high-voltage passive probes with a signal attenuation of 100x. Some important specifications for these probes are as follows:

Attenuation: 100x within 3%(including 1MΩ ± 2% amplifier input).
Input Resistance: 10 M Ω within 2%.
Input Capacitance: Approximately 2.5 pf.
Compensation Range: 15 pf or less to at least 47 pf..
Bandwidth (-3dB): At least 120 MHz.
Maximum Input Voltage: 1.5 kV (DC or RMS).

b) Amplifiers and Filters:

The amplifiers and filters used in this system are Tektronix 1121, and Kron-Hite model 3200 respectively. These are identical to amplifiers and filters reported by J. R. Roth and W. M. Krawczonek.[3]

c) Transient Recorders:

The analog signals from the filters are converted into digital form by two TR8837 transient recorders. These transient recorders are capable of sampling up to 32 megasample/second, and storing digitized signals sequentially in a dedicated 8K-x-8-bit memory. The user may program the system to use only a fraction of this memory. The amount of dedicated memory actually used is called the active memory or record length. When the recorder fills the active memory, it continues to digitize until a stop trigger is received. Upon stopping, the transient recorder informs the host computer that it has data available. The host computer then reads, stores, and displays the data.
Listed below are the summarized specifications for the transient recorders. For detailed specifications refer to reference (4).

Signal Range: 512 mv peak to peak.

Offset: The input signal offset is adjustable via a front panel potentiometer.The offset range is ± 256 mv.

Bandwidth: > 16 MHz (1dB) for amplitude up to t the full 512 mv signal range.

Impedance: 50Ω ± 1%, 12 pf.

Conversion clock: Internal clock frequency of 32, 16, 8, 4, 2, 1 or 0.5. MHz, or external clock.

Resolution: 8-bits (1 part in 256).

d) Central Units:

A three microprocessor (main, arithmetic, and display) memory board with 64k bytes of memory, histogram data memory boards, and Quad serial communication board constitute the central units of the LeCroy 3500 SA signal analyzer.

The main or central processor is an 8085A microprocessor. An 8085 A microprocessor is also dedicatd to display operation. An AM 9511 is the arithmetic processor unit which provides 32-bit floating point calculations. The histogram data memory board includes 8192 channels of 24-bit count capacity per channel. The Quad Serial communication board provides four RS-232-C ports for communication with other computers. For a detailed description of these units refer to reference 5.

B. SOFTWARE

The software necessary for this system to obtain the desired results consists of three different programs. The first program (JOB1), which is written in Fortran 80, is an interactive program. This program, by itself, performs three different functions. The program first opens a data file on the disk residing in drive B, then prompts the user for memory size and the starting memory channel for the appropriate experiment (in this case two transient recorders require 4k byte of memory with starting memory location at channel zero). As its second function, the program prompts the user for various fiduciary experimental parameters such as date, file number, anode voltage and current, magnetic field, and pressure, all entered in appropriate units. In this part, the program also asks the user to enter the front panel settings for each transient recorder. Some examples of these selections are input range setting for each transient recorder and sample interval. As its third function, program Job1 reads the input values of two transient recorders directly from the histogram memory of the computer and stores these values along with fiduciary data on the data file which has already been opened on a floppy disk in drive B. Figure 2 is a flowchart for this program. This program is run on the LeCroy 3500 SA. Further details may be found in Reference 7.

The second program is the digital time series analysis program. This program, which was written by Jae. Y. Hong[1], makes extensive use of the Fast Fourier Transform (FFT). This program was modified for compatibility with the other two programs written for this system. The original program uses Calcomp plotting subroutines to plot various spectra. The modified program, which is run on the VAX 11/780 system, opens a data file and stores the processed data for each spectrum. This processed data is then sent to the LeCroy 3500/SA system for plotting. The LeCroy system has its own plotting subroutine. Figure 3 is a simplified flowchart for this program. For detailed explanations of this program refer to references 1 and 3.

The third program, Job2, is written in Fortran 80. This program reads the processed data coming from the VAX 11/780 to the LeCroy and plots various spectra such as auto-power spectrum of channels 1 and 2, cross amplitude spectrum, phase spectrum, and squared coherency spectrum of channels 1 and 2. This program also plots the inputs for channel 1 and 2 in the time domain. Program JOB2 screen dumps the plots to the printer for later viewing. Figure 4. shows a flowchart for this program. Further details are available in Reference 7.

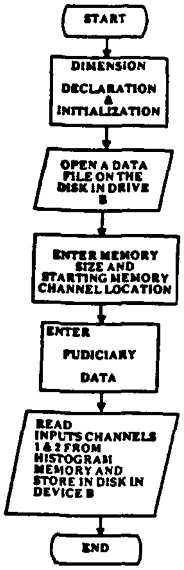

Figure 2. Flowchart for program job1.

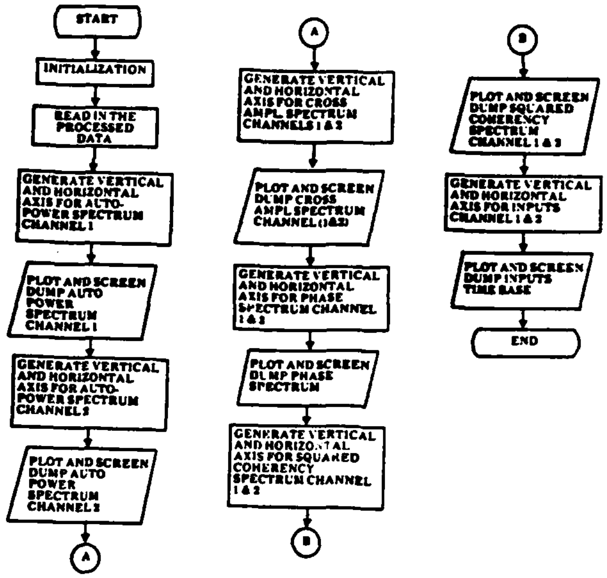

Figure 4. Flowchart for program job2.

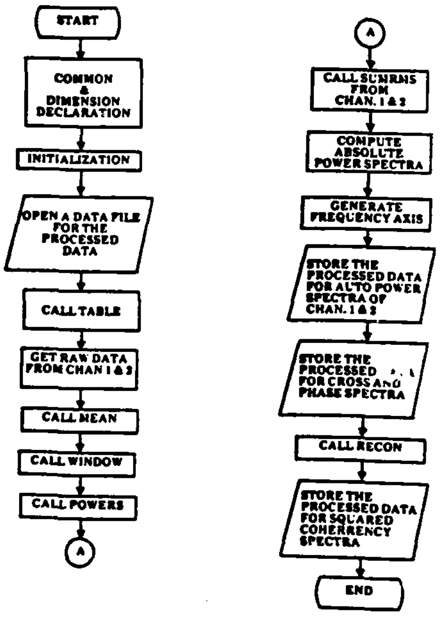

Figure 3. Flowchart for program TEST77.

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DATE: 10/26/85
RUN NUMBER: APD5
ANODE VOLTAGE (KV): 1.30
ANODE CURRENT (AMP): .002
MAX. MAGNETIC FIELD (TESLA): .440
PRESSURE (MICROTORR): 30.0
AVERAGE PLASMA NUMBER DENSITY (ELECTRONS/ (M**3)): 1.00*10**14
RADIAL POSITION OF PROBES FROM THE CENTER OF PLASMA (CM): 10.0
MICROWAVE SCATTERING ANGLE (DEGREE): 999.9

CHANNEL NO.1 DATA.
INPUT RANGE SETTING: .512
SAMPLE INTERVAL (MICROSEC): 1.000
ANTIALIAS FILTER (MHZ): 0.000
OVERALL PROBE GAIN (VOLT): .150

CHANNEL NO.2 DATA.
INPUT RANGE SETTING (VOLT): .512
SAMPLE INTERVAL (MICROSEC): 1.000
ANTIALIAS FILTER (MHZ): 0.000
OVERALL PROBE GAIN (VOLT): .150

CHANNEL NO.3 DATA.
INPUT RANGE SETTING (VOLT): 0.000
SAMPLE INTERVAL (MICROSEC): 0.000
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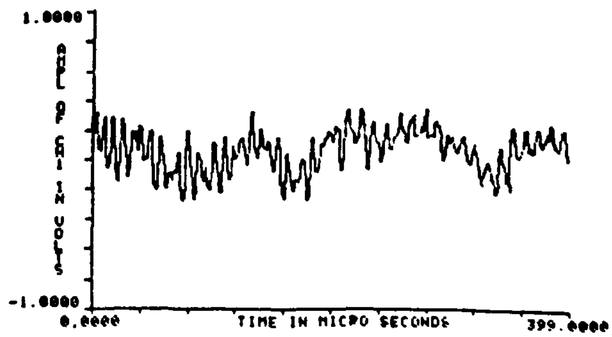
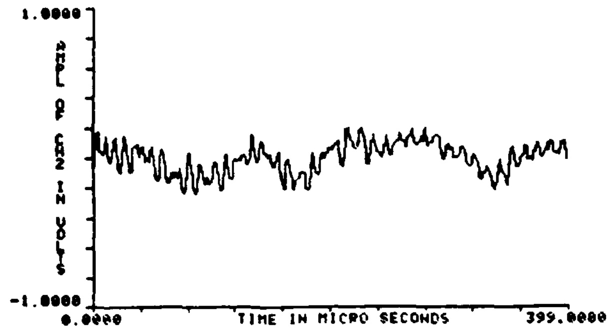
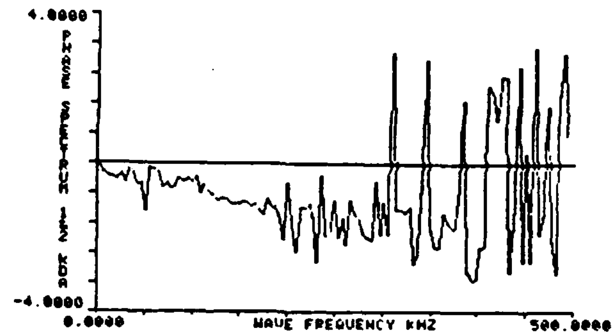
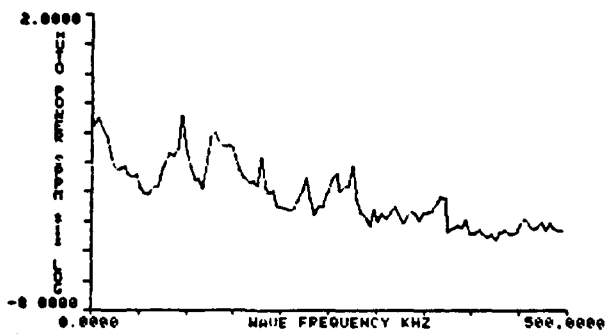
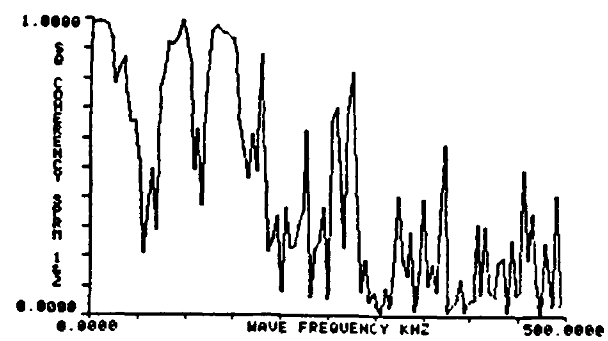
D.C. VOLTAGE AT PREAMP INPUT (VOLT): 0.00
ADDITIONAL COMMENTS ?

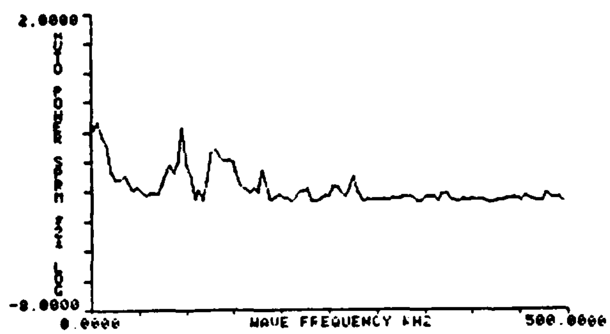


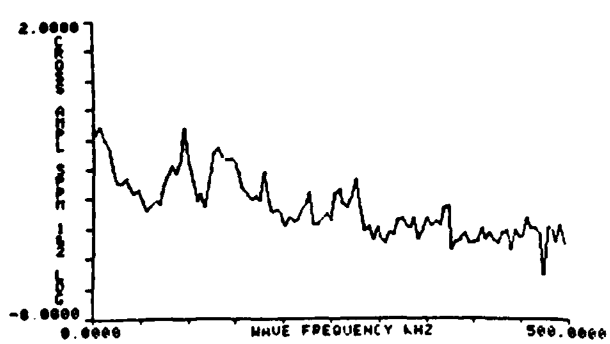












This work was supported by the Office of Naval Research under Contract ONR N-00014-80-C-0063. Copies of Reference 7 may be obtained by direct request to the authors.

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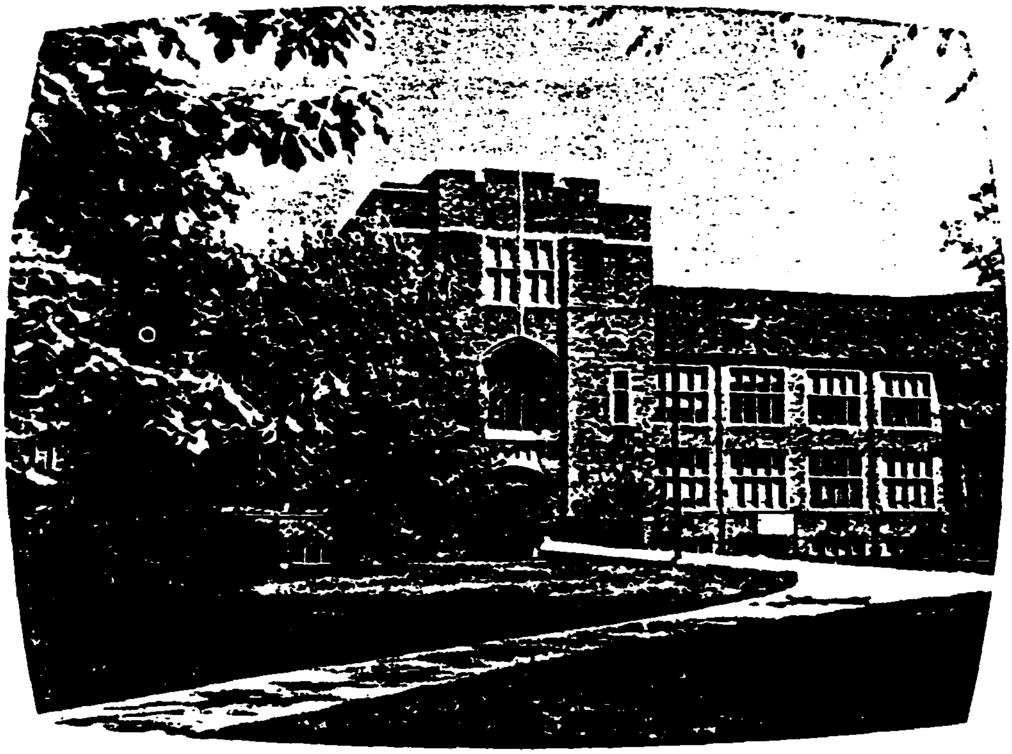

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EDGE TURBULENCE STUDIES ON A MODIFIED PENNING DISCHARGE*

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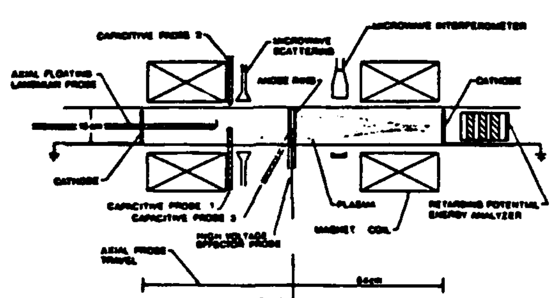
ABSTRACT

The edge region of a magnetically confined hot plasma is characterized by large temperature and density gradients. These gradients act as energy reservoirs for various nonlinear instabilities resulting in drift waves[1] and broadband edge turbulence. Drift waves in a turbulent plasma are typically quasiperiodic with finite coherence lengths. When externally enhanced these waves can have increased coherence lengths and exhibit strong mode coupling, with the number of observed harmonics doubling. Increased background turbulence, electron heating and modification of the spectral index are observed[2]. Under special conditions using a subharmonic external signal, drift modes and background turbulence have ben damped. Increased electron temperature and number density are observed with damping.

INTRODUCTION

The UTK Plasma Lab operates a steady state modified Penning discharge capable of electron number densities of up to a few $10^{10}/cm^3$, at electron temperatures of 10 to 100 eV. The 60 cm long discharge consists of an anode ring and two cathode end plates (see Fig. 1). The confining magnetic field has a 5.1 to 1 mirror ratio with the maximum field variable up to 0.33 tesla. A glass vacuum vessel surrounds the discharge and allows external detection of the electrostatic fluctuations associated with the turbulence and drift waves on the edge of the plasma. The base pressure of the system is typically 6 microtorr, with operating pressures of around 100 microtorr.



MODIFIED PENNING DISCHAGE
(TOP VIEW)

fig. 1

At the midplane of the discharge a tungsten probe is inserted radially thru the anode ring. This "effector probe" is D.C. biased to the anode potential and is A.C. coupled to either a full sine wave or a positive half rectified sine wave. A Ling power amplifier capable of up to 1.0 amp at 5 kilovolts over the frequency range 0.5 to 100 kHz is used to drive the effector probe for turbulence enhancement and damping studies.

Electrostatic fluctuations of the plasma edge are detected using capacitive probes located the glass vacuum vessel. Detected signals in the frequency range 0.01 to 2 MHz are amplified and viewed on a spectrum analyzer, microwave network analyzer, or digitaly sampled using a LeCroy 3500 signal processing system. Under conditions having a high degree of coherence the microwave network analyzer yields the phase informaiton between two probes. This phase information can be related to the direction and velocities of wave propagation. Digital time series analysis of the transient samples of these signals is also performed to yield auto and cross power spectra, and phase and coherency spectra.

EXPERIMENTAL DATA

Auto power spectra for typical plasma conditions with and without external excitation are shown in Figure 2. The self excited spectrum (APK1) was taken on probe 1 with an anode voltage of 4400 volts and current of 38 mA. The enhanced spectrum is taken while a 68 kHz, 1kV, 5 mA_{peak} half wave rectified signal is applied to the effector probe. The enhanced spectrum is as much as 20 dB above the self excited level. Highly nonlinear mode coupling is exhibited here due to the continuous "filling" of the spectrum. Note that energy is cascading both upward and downward in frequency space.

Figure 3 thru 6 show the phase and coherency spectra for the spectrum shown in Figure 2, and for a similar spectrum for signals taken by a second probe located azimuthally 60° from probe 1. For the enhanced turbulence, Figures 4 and 6 show increased coherency and a linear phase spectrum, yielding a well defined group velocity of approx. 5×10^4 m/sec. The high level of coherency in Figure 4 is a requirement for a meaningful phase spectrum. The apparent spikes on Figure 6 are due to the software programs inability to distinguish btween $\pm$ 180°, with some finite noise level causing the spectrum to flip back and forth.

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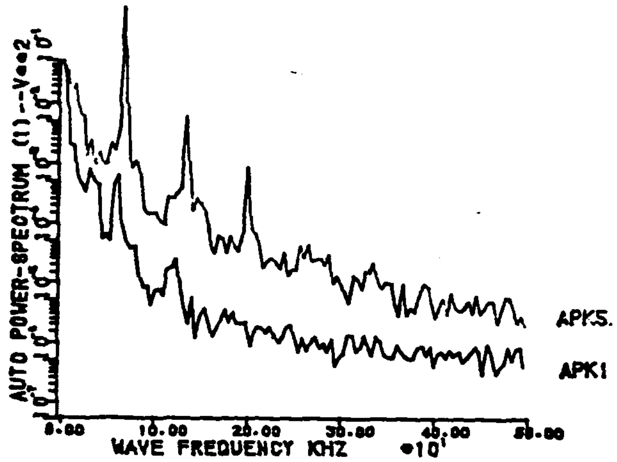

fig. 2

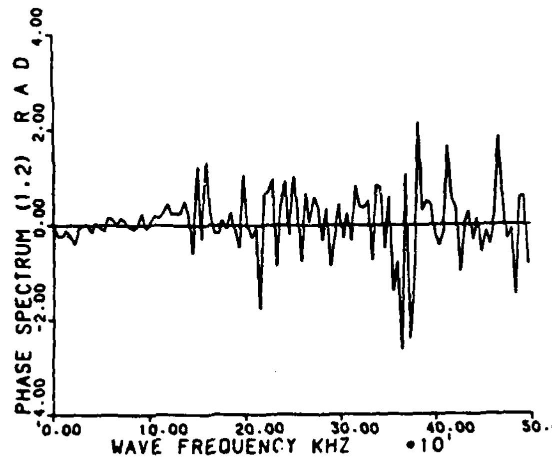

fig. 5

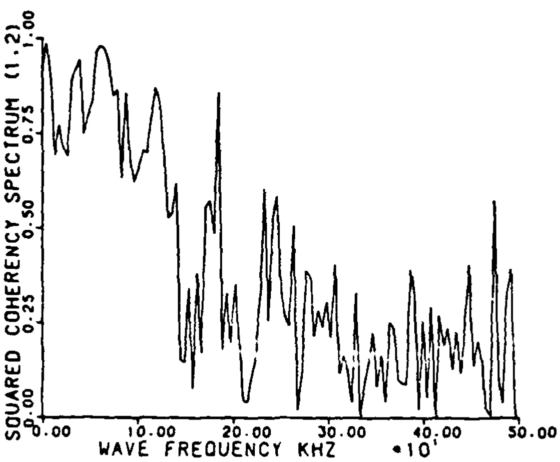

fig. 3

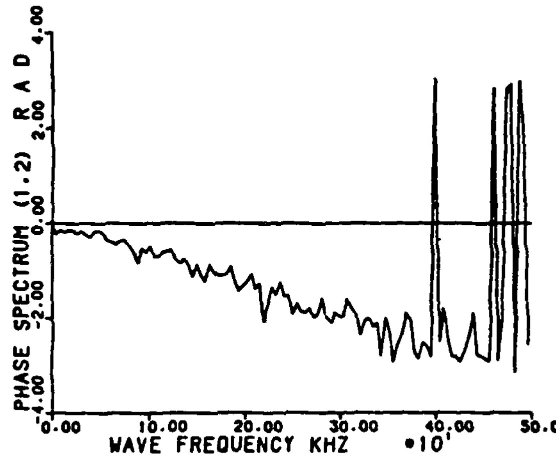

fig. 6

Figures 7 and 8 show the effect of using a low frequency (3.4 KHz, 4 kv_{pp}, 5 mA full sine wave) to damp a high frequency mode. Electron heating and increased number density were observed with damping. Although the high frequency mode is clearly damped in Figure 8, some enhancement at the low frequency is evident. The effect of damping is extremely critical in terms of the amplitude and frequency of the effector signal. Variation in frequency of a few percent will produce an enhanced spectrum. The signal amplitude had been carefully adjusted to yield optimum damping for Figure 8.

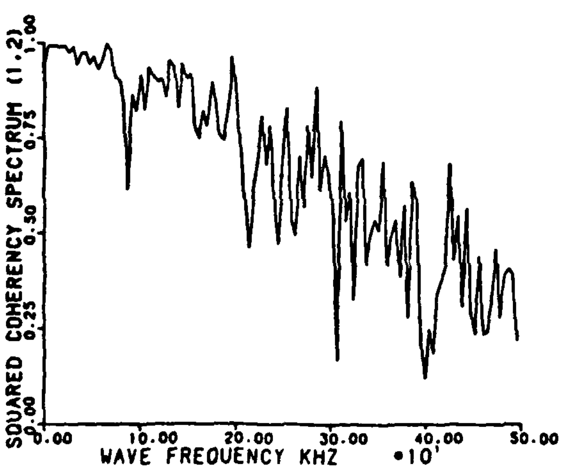

fig. 4

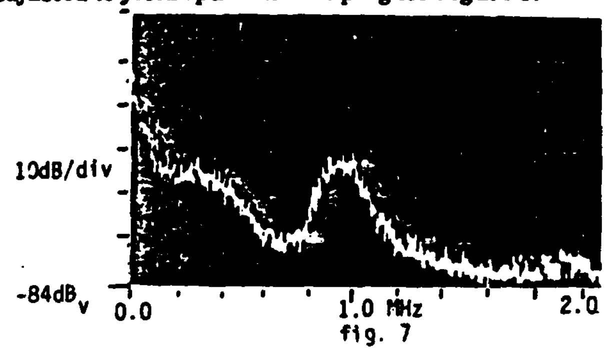

fig. 7

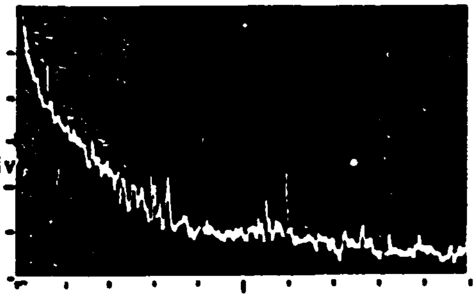

fig. 8

CONCLUSION AND DISCUSSION

The electrostatic signal detected from the edge turbulence on a Penning discharge indicates a wide range of phenomena, from quasiperiodic to fully turbulent. The addition of an effector probe to the discharge allows the plasma to be perturbed by a coherent signal resulting in enhancement or damping. The energy cascade mechanism under a controlled perturbation can now be studied under a variety of plasma conditions.

ACKNOWLEDGEMENTS

This work is supported by the Office of Naval Research Contract ONR N00014-80-C-0063

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Spence, P. D. and Roth, J. R.: "Active Modification of Plasma Turbulence with an EFfector Probe". Proc. of the 18th International Conf. on Ionization Phenomena in Gases, Swansea, Wales, 13-17 July, 1987

ACTIVE MODIFICATION OF PLASMA TURBULENCE WITH AN EFFECTOR PROBE

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Abstract

The edge region of a magnetically confined hot plasma is characterized by large temperature potential and density gradients. These gradients drive various nonlinear instabilities resulting in drift waves [1] and broadband edge turbulence. Drift waves in a turbulent plasma are typically quasiperiodic with finite coherence lengths. When externally enhanced, these waves can have increased coherence lengths and exhibit strong mode coupling, with an increase in the number of observed harmonics. Increased background turbulence, electron heating and modification of the spectral index are observed [2]. Under special conditions using a subharmonic external signal, drift modes and background turbulence have been damped. Increased electron temperature and number density are observed with damping.

Introduction

The UTK Plasma Laboratory operates a steady state modified Penning discharge capable of electron number densities of up to a few $10^{10}/cm^3$, at electron temperatures of 10 to 100 eV. The 60 cm long discharge consists of an anode ring and two cathode end plates (see Fig. 1). The confining

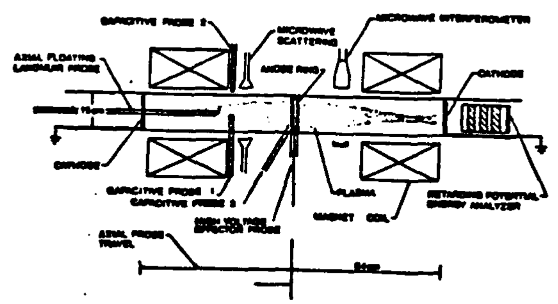


Figure 1. Schematic of the Modified Penning Discharge.

magnetic field has a 5.1 to 1 mirror ratio with the maximum field variable up to 0.33 Tesla. A glass vacuum vessel surrounds the discharge and allows external detection of the electrostatic fluctuations associated with the turbulence and drift waves on the edge of the plasma. The base pressure of the system is typically 6 microtorr, with operating pressures of around 100 microtorr. Helium gas was used for the data discussed.

At the midplane of the discharge a tungsten probe is inserted radially thru the anode ring. This "effector probe" is DC biased to the anode potential and is AC coupled to either a full sine wave or a positive half rectified sine wave. A Ling power amplifier capable of up to 1.0 amp at 5 kilovolts over the frequency range 0.5 to 100 kHz is used to drive the effector probe for turbulence enhancement and damping studies. Input power from the probe to the plasma is typically 5% to 15% of the DC input power.

Electrostatic fluctuations of the plasma edge are detected using capacitive probes located on the glass vacuum vessel. Detected signals in the frequency range 0.01 to 2 MHz are amplified and viewed on a spectrum analyzer, a network analyzer, or digitally sampled using a LeCroy 3500 signal processing system. Under conditions having a high degree of coherence, the network analyzer yields the phase information between two probes. This phase information can be related to the direction and velocities of wave propagation. Digital time series analysis of the transient samples of these signals is also performed to yield auto and cross power spectra, and phase and coherency spectra.

Physical Processes in the Plasma Sheath

A cross sectional view of the plasma at the anode is shown in Figure 2. Both the radial electric field (due to the

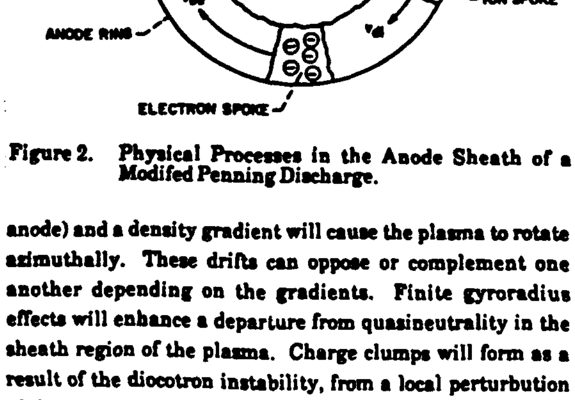


Figure 2. Physical Processes in the Anode Sheath of a Modifed Penning Discharge.

anode) and a density gradient will cause the plasma to rotate azimuthally. These drifts can oppose or complement one another depending on the gradients. Finite gyroradius effects will enhance a departure from quasineutrality in the sheath region of the plasma. Charge clumps will form as a result of the diocotron instability, from a local perturbution of the radial electric field (or density gradient). Ion and/or electron spokes will propogate azimuthally producing periodic potential variations for detection by a stationary capacitive probe.

The effector probe consists of a tungsten filament

inserted radially at the anode. This probe was intended to couple to and drive an existing E x B spoke. This probe has axial and azimuthal electric field components, as well as a radial component. Coupling to a ∇n drift wave is assumed to be through the modulation of the potential ϕ in a Boltzmann distribution, where

$$n(r) = n_o(r)\exp\left(\frac{e\phi}{T_e}\right) \approx n_o(r)\left(1 + \frac{e\phi}{T_e}\right) \qquad (1)$$

Experimental Data

Auto power spectra for typical plasma conditions with and without external excitation are shown in Figure 3. The

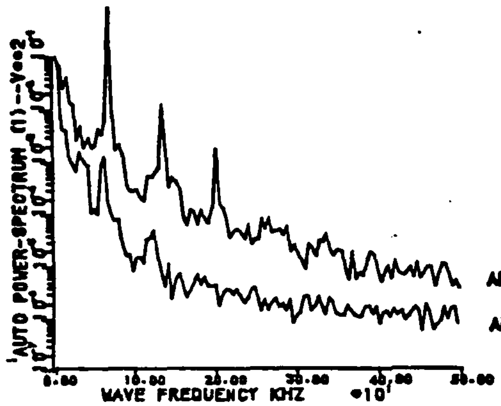
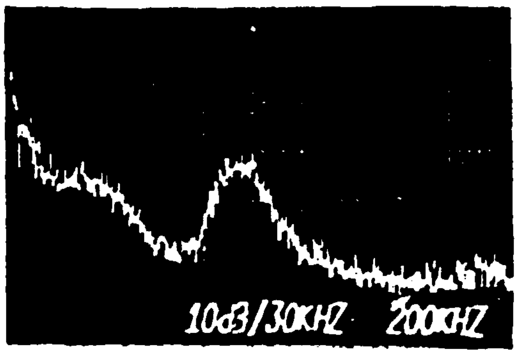


Figure 3. Auto power spectra of electrostatic potential fluctuations from 0 to 500 kHz. Run APK1, self-excited modes. RUN APK-5 enhanced spectrum with signal on effector probe.

self excited spectrum (APK1) was taken on probe 1 with an anode voltage of 4400 volts and current of 38 mA. The enhanced spectrum is taken while a 68 kHz, 1 kV, 5 mA_{peak} half wave rectified signal is applied to the effector probe. The enhanced spectrum is as much as 20 dB above the self excited leve'. Highly nonlinear mode coupling is exhibited here due to the continuous "filling" of the spectrum. Note that energy is cascading both upward and downward in frequency space.

Load pulling is an additional feature exhibited with the enhancement of a self excited mode by a signal on the effector probe. The external oscillator can pull the self excited mode



linear frequency scale

Figure 4. Self-excited modes in the plasma over the range 0-2.0 MHz.

frequency as much as 50%. Greater detuning results in decoupling of the probe from the self excited mode and a loss of the enhanced spectra.

Figures 4 and 5 show the effect of using a low frequency (3.4 KHz, 4 kV_{pp}, 5 mA full sine wave) to damp a high frequency mode. Electron heating and increased number density were observed with damping. Although the high frequency mode is clearly damped in Figure 5, some enhancement at low frequencies is evident. The effect of

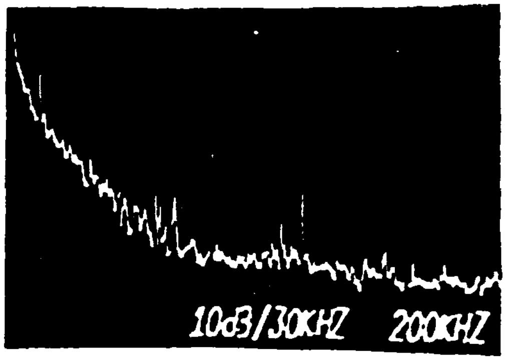


Figure 5. Same plasma conditions as Figure 4, with mode damping resulting from a 3.4 kHz signal on the effector probe.

damping is extremely critical in terms of the amplitude and frequency of the effector signal. Variation in frequency of a few percent will produce an enhanced spectrum. The signal amplitude had been carefully adjusted to yield optimum damping for Figure 5.

Conclusion and Discussion

The electrostatic signal detected from the edge turbulence on a Penning discharge indicates a wide range of phenomena, from quasiperiodic to fully turbulent. The addition of an effector probe to the discharge allows the plasma to be perturbed by a coherent signal resulting in enhancement or damping. The energy cascade mechanism under a controlled perturbation can now be studied under a variety of plasma conditions.

The damping of self excited oscillation by external forcing is discussed in systems with one and two degree's of freedom by V. Migulin, [3] N. Minorsky [4]. Systems with cubic or quadratic nonlinear dissipation terms can have jumps in amplitude of the self excited mode under external excitation. This suggests the presence of a nonlinear dissipation mechanism in this experiment, where similar phenomena have been observed.

Acknowledgements

This work is supported by the Office of Naval Research Contract ONR N00014-80-C-0063.

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MEASUREMENT OF THE EFFECTIVE MOMENTUM COLLISION FREQUENCY IN A TURBULENT, WEAKLY IONIZED PLASMA

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Introduction

Electron cyclotron resonance absorbtion measurements have been made on a weakly ionized, steady-state, turbulent plasma using a Hewlett Packard 8510 Network Analyzer. This instrument is capable of swept frequency measurements of reflection and transmission coefficients from 0.045 to 18 GHz, with greater than 80dB dynamic range. The absorbtion measurements near electron cyclotron resonance are interpreted in terms of numerical solutions of the Appleton equation [1] to yield an "effective" collision frequency equal to the full width of the absorbtion curve at twice the resonance minimum. A two channel homodyne microwave scattering system (f_o = 14 GHz) is used along with a capacitive probe to measure turbulence levels. Axial and radial Langmuir probes are used for electron number density and kinetic temperature measurements.

The Classical Penning discharge used to generate the plasma (see Figure 1) consists of a uniform magnetic field with a maximum value of 0.195 Tesla. The field is uniform to within 3% between anodes. An approximately 12 cm diameter steady state plasma column is generated which is 118 cm long. This plasma had a characteristic density of a few times 10^9 electrons/cm^3, electron kinetic temperatures of 10 eV to 100 eV, and helium ion kinetic temperatures of several hundred eV[2,3].

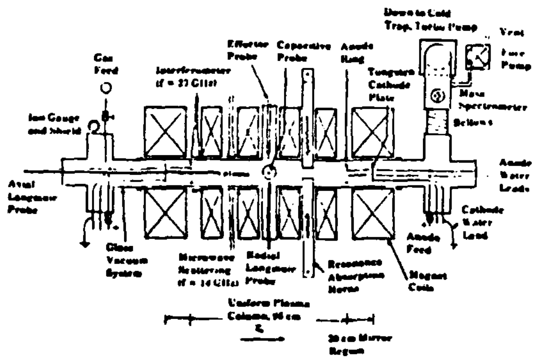

Figure 1 Plan View of Penning Discharge, with Diagnostic Equipment.

Measurements

Signals from the capacitive probe and the microwave scattering system were amplified and bandpass filtered. Both signals were processed by a Tektronix 7L5 spectrum analyzer. The turbulence spectrum power levels are measured using a Boonton model 91-12F RF detector. High pass filtering is 100kHz with low pass at 2 MHz. The apparatus was adjusted to try to maintain signal (power) levels at least 10 dB above the noise levels. The antenna geometry for the electron cyclotron resonance absorbtion measurements made on this plasma is shown in Figure 2 below,

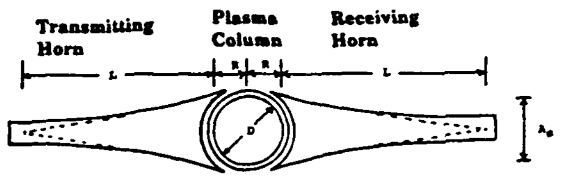

Figure 2 Cross-sectional view of Microwave Antenna Geometry for ECR Measurements in the Range 2-10 GHz. In this experiment, L = 34 cm, R = 6 cm, D = 12 cm, and A_g = 12 cm.

Figure 3 shows a characteristic absorbtion curve on the top, and the phase angle on the bottom. The sweep time for these traces is 500 msec with 10 traces averaged. Itis desired that an electron remain in the beam sufficiently long to damp the absorbed energy by collisions rather than transport it out of the beam region by axial motion at the thermal velocity. For all data reported here, the product $\tau_e \nu_{eff} > 1$, implying that electrons made at least one collision while they were in the microwave probing beam.

The Effective Collision Frequency

The Appleton equation is a hydromagnetic equation relating a Lorentz collision term in a cold plasma to the propagation constants of an electromagnetic wave [1]. Numerical solutions to it were obtained for characteristic plasma conditions such as Figures 3; in general, it was found that the numerical solution had a resonance curve much narrower than the experimental data, and that the data often exhibited secondary absorbtion peaks or "plateaus" (like Figure 3) which were not predicted by the Appleton equation. This may be a non-linear mode coupling or a hot plasma effect.

Galeev and Sagdeev [4] introduce an effective collision frequency based on Langmuir turbulence (no magnetic field present);

$$\nu_e = \omega_{pe} \frac{W}{n_e T_e}, \tag{1}$$

where W is the energy density of waves in the region of interest with wavelengths on the order of the Debye radius.

For drift wave turbulence Horton [4] derives the total fluctuation energy density

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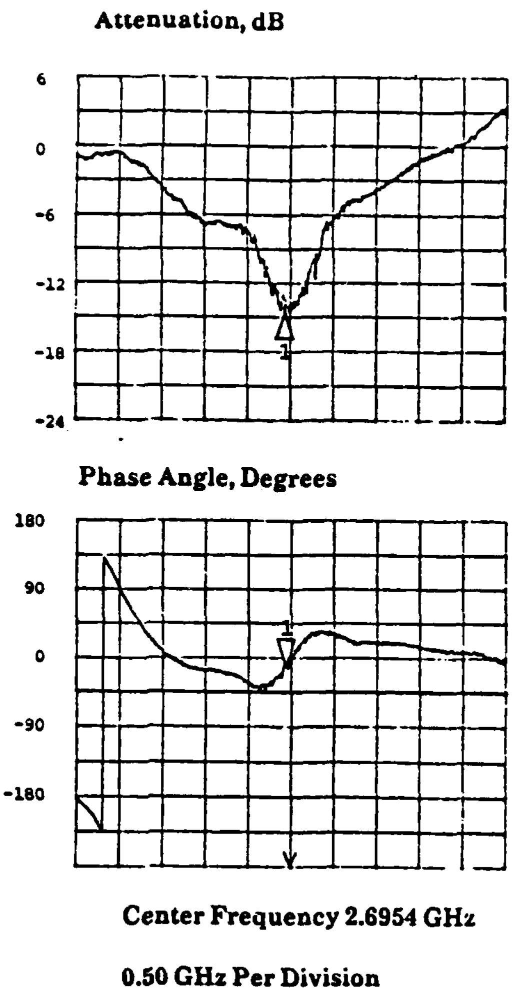

Figure 3 Electron cyclotron resonance absorbtion (top) and phase angle (bottom), for a maximum absorbtion at 2.689 GHz (triangle) and a full width at half maximum (3 dB above minimum) of v_{eff} = 47.5 MHz.

$$W = \sum_k W(k) = \frac{e^2 n_e}{2T_e} \int dk \left[|\phi(k)|^2 + \left(\nabla_\perp \phi(k) \right)^2 \right] \qquad (2)$$

The capacitive probe will measure a function of $\phi(k)$ with the scattering power related to $\nabla_\perp \phi(k)$. Since neither the capacitive probe or the microwave scattering are absolutely calibrated, v_s is plotted in Figure 4 as a function of

$$v_s \sim \frac{n_e^{3/2}}{n_o T_e^2} P, \qquad (3)$$

where P is the integrated power spectra for either the capacitive probe spectra or the microwave scattering spectra, and n_o is the neutral background density. Figure 4 indicates a disagreement of our data (v_{eff}) with the theory of Galeev and Sagadeev as elaborated by Horton [4] (v_s), since the data do not lie along a straight line with a 45° slope, showing a linear proportionality.

Conclusions

The measured effective collision frequency was consistently larger than the calculated electron-neutral

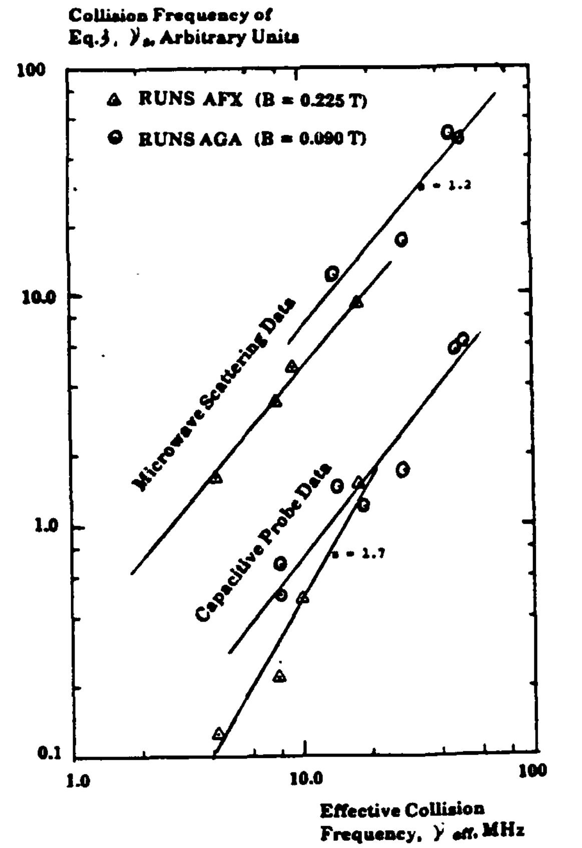

Figure 4 Collision frequency of Galeev and Sagdeev [4], v_s (Eq. 1) plotted against the effective collision frequency, v_{eff}, from ECR absorbtion measurements.

collisional values, using the cross section at 10 eV. The effective collision frequency is as much as 20 times the binary, Lorentzian value. This increase in collision frequency is very probably due to electron scattering by plasma turbulence.

The use of a hydromagnetic equation avoids any Landau damping effects. However, two minima have been observed in the resonant absorbtion curves, indicating possible hot plasma effects (see Figure 3). The broad resonance curves and large phase shifts, as the double minima, indicate that a hydromagnetic treatment is not sufficient, although it does provide a good first approximation.

Acknowledgement

Experimental work supported by ONR Contract N00014-80-C-0063; Key equipment was supplied by AFOSR Grant 85-0152.

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APPENDIX F

Bibliography of Oral and Poster Conference Presentations Supported by ONR Contracts N00014-80-C-0063 and N00014-88-K-0174

Bibliography of Oral and Poster Conference Supported by Contracts ONR N00014-80-C-0063 and N00014-88-K-0174

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APPENDIX G

Abstracts of Oral and Poster Conference Presentations Supported by ONR Contracts N00014-80-C-0063 and N00014-88-K-0174

3H3 A New Mechanism for Electromagnetic Emission and Anomalous Resistivity from Equal and Oppositely Directly Electron Beams Interacting with Heavy Ions.*

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We present an extension of recently-reported work[1] on the experimental observation and theoretical description of a previously unrecognized mechanism for generating electromagnetic emissions from a Penning-discharge-like beam-plasma interaction. These emissions were observed from the electric field dominated NASA Lewis bumpy torus plasma in excellent agreement with the theoretical frequency

$$\omega_{gm} = \frac{(\omega_{pe}\omega_{pi})^{1/2}}{\sqrt{2}\sqrt[4]{3}} = .537\ \omega_{pe}\left(\frac{m}{M}\right)^{1/4} \qquad (1$$

which differs from the well-known Buneman frequency[2] by the factor

$$\frac{\omega_{gm}}{\omega_B} = \frac{2^{4/3}}{\sqrt{2}\sqrt[4]{3}}\left(\frac{M}{m}\right)^{1/12} = 2.53A^{1/12} \qquad (2$$

Where A is the atomic weight of the heavy ions. This frequency is emitted over a very narrow window in wavenumber, and may be derived from a theory based on the interaction of two opposite, interpenetrating electron beams with a cold heavy ion plasma. A perturbation procedure is used to obtain analytic expressions for the emission frequency and anomalous resistivity in the zero temperature case. The anomalous resistivity associated with this interaction is predicted to be several hundred times that of the familiar Buneman or "turbulent" resistivity. These high anomalous resistivities may offer an explanation for the very high radial and/or axial electric fields - sometimes in excess of 1 kV/cm - which have been observed in Penning discharges[3,4], and in the Electric Field Bumpy Torus Plasma[5].

The perturbation results are extended by direct numerical computation of the dispersion relation with a finite ion temperature term included. The effects of finite ion temperature on the dispersive properties of the two interpenetrating beam interaction, and on the anomalous resistivity of the plasma, are discussed. Finite ion temperatures have the effect of reducing the frequency bandwidth of the emissions to a fairly narrow range of frequencies. The small bandwidth in frequency and wavenumber is consistent with the experimentally observed narrow emission peak reported in reference 1.

* Preparation of this paper was supported in part by ONR Contract #N0014-80-C-0063, and in part by NSF Grant ENG-78-03400.

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511 Anomalous Conductivity of an Electric Field Bumpy Torus Plasma. J. REECE ROTH, Department of Electrical Engineering, University of Tennessee, Knoxville, TN 37916.

The electric field bumpy torus plasma operates in the steady state under the influence of a DC toroidal magnetic field, and strong externally imposed DC electric fields along the minor radius of the plasma[1]. The entire toroidal ring of plasma can be biased to high positive or negative potentials by one or more electrodes located at the midplanes of each sector. It has been found that this plasma is characterized by a high degree of fluctuation-induced radialtransport[2,3], radial electric fields which can reach values of 1 kilovolt/centimeter, radial scale lengths on the order centimeters for both density and electric field, and penetration of these electric fields into the vicinity of the plasma axis. The two-interpenetrating-beam instability[4], or the Buneman instability[5] are capable of explaining very low plasma conductivities along the magnetic field in this plasma and in Penning discharges; the mechanism for the very low cross-field conductivity and the presence of strong radial electric fields required investigation.

The cross-field conductivity and radial transport mechanism were experimentally investigated by measuring the functional dependence of the plasma resistance (defined as the electrode voltage/electrode current) on several geometric and plasma parameters. It was found that the plasma resistance is inversely proportional to plasma electron number density. At a given number density, the resistance is about forty times higher for negative polarity (when the electrodes collect ions) than for positive polarity. When the number of biasing electrodes was varied, it was found that for negative polarity, the resistance was inversely proportional to the number of electrodes, but independent of number of electrodes for positive polarity. This implies that the plasma resistance is determined by processes in the negative electrode sheath where ions are collected from the plasma. It was found further that the plasma resistance was independent of toroidal magnetic field strength (very unlike Bohm or classical diffusion), and independent also of background neutral gas pressure. These observations rule out Bohm or classical diffusion, and the Pedersen conductivity, which results from binary collisions and is in the direction of the radial electric field.

The mechanism which is consistent with these observations is that the negative electrode is acting like a large Langmuir probe in ion saturation, and that fluctuation-induced transport[2,3] in its sheath is so rapid that the entire kinetic theory flux of ions, $j = nev/4$, reaches the electrode surface as though the magnetic field were not present at all.

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9U 12 RF Emissions from Beam-Plasma Interactions in a Modified Penning Discharge.* J. REECE ROTH, Department of Electrical Engineering, University of Tennessee, Knoxville 37916.

A modified Penning discharge[1] has been set up in a magnetic mirror configuration with a mirror ratio of 5:1, maximum magnetic fields of 0.4 tesla, and electrode voltages up to 10 kV DC. A discharge has been operated in several background gases at electron number densities which are characteristically $10^{10}/cm^3$. The high mirror ratio was chosen to better simulate the situation along flux lines in the earth's magnetosphere. The electron population trapped in the discharge is thought to consist of two interpenetrating beams of electrons, which should be capable of exciting the geometric mean plasma emission[2]. The RF spectrum of this discharge is characterized by a rich variety of emission peaks below 200 MHz, at least one of which may be the geometric mean emission frequency. Sideband generation and other nonlinear coupling phenomena are very much in evidence.

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1Q2 ION MASS DEPENDENCE OF RF EMISSIONS AT THE GEOMETRIC MEAN PLASMA FREQUENCY*

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Radio frequency emissions in the vicinity of the geometric mean plasma frequency[1] have been observed from an electric field dominated plasma generated in a modified Penning discharge[2]. The geometric mean plasma frequency arises when two interpenetrating beams of electrons interact in a background of relatively cold ions[1]. The frequency of this emission is predicted theoretically to be

$$\omega_{gm} = \sqrt{\omega_{pe}\omega_{pi}} / 2^{\frac{1}{2}} 3^{\frac{1}{4}} = 0.537 \sqrt{\omega_{pe}\omega_{pi}} .$$

This expression has been found to be in excellent agreement with emissions from the Lewis Electric Field Bumpy Torus plasma[1]. The predicted dependence on the ion mass has not been tested experimentally heretofore, and this was the main thrust of the quantitative observations described in this paper.

The modified Penning discharge used in this investigation is generated in an axisymmetric magnetic mirror field with a 5:1 mirror ratio. This relatively large value was chosen to better simulate conditions in the earth's magnetosphere, where this emission process may also occur. A positive midplane electrode ring with an inside diameter of 12 cm defined the midplane diameter of the plasma. This anode was biased to potentials of one to ten kilovolts. Strong electric fields, up to hundreds of volts per centimeter, penetrate the plasma axially and radially through physical processes that are for the most part poorly understood at present. Electrons in this plasma find themselves in a classic Penning potential well, and oscillate back and forth along axial magnetic field lines. These electrons then constitute two interpenetrating beams at the midplane, where their kinetic energy is greatest.

RF emissions were observed from this plasma at frequencies consistent with the geometric mean emission process over a significant range of operating conditions. Emission data were taken for a range of background gases to test the predicted inverse fourth root mass dependence. It was found that preliminary data were consistent with this dependence. An experiment was performed in which the proportion of helium and argon in the background was varied continuously from zero to 100% and back again to zero. The results indicated that the geometric mean emission peak appeared separately at frequencies appropriate for each gas, with the amplitude of each being proportional to the gas concentration. There was not, in these experiments, a single peak which moved in frequency in proportion to the average ion mass in the emitting plasma.

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9T 11 RF Emission, Nonlinear Mode Coupling, and Ion Thermalization in a Modified Penning Discharge Plasma*.

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We report new data on RF emissions and nonlinear mode coupling from a low density (below 10^{10}/ cm^3) electric field dominated plasma[1] which possesses strong radial and/or axial electric fields, and was confined in a high magnetic mirror ratio configuration. We also investigated, in this magnetospheric-like plasma, the process of ion thermalization as a function of the magnetic field strength and particle number density. It was found that the degree of nonlinear mode coupling in the RF spectrum increased with increasing magnetic field strength, and that the degree of ion energy thermalization (measured with a retarding potential energy analyzer) increased with the level of RF activity, and was greater at lower particle number densities. The dominant RF emission peak in this plasma appears to be the geometric mean plasma emission.[2]

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1G 8 Radial Equilibrium and Force Balance in Electric Field Dominated Plasmas. J. REECE ROTH*, Department of Electrical Engineering, University of Tennessee, Knoxville, TN 37916*.

This paper is concerned with the effect of strong radial electric fields on the equilibrium and stability of mirror and bumpy torus plasmas such as the modified Penning discharge[1] and the Electric Field Bumpy Torus (EFBT)[2]. These devices have radial electric fields which can reach levels of kilovolts per centimeter. In such a case, the electric field force on a charged particle can be larger than, and opposite to, the centrifugal forces arising from transit of the particle over the midplane bump in the region of bad curvature. The conditions leading to such a force balance are derived. Devices such as the modified Penning discharge and the EFBT are electric field dominated, and are experimentally observed not to be subject to low frequency MHD instabilities under the predicted conditions[3].

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3E1 A PAIRED COMPARISON OF HIGH FREQUENCY RF EMISSION FROM TWO CONFIGURATIONS OF ELECTRIC FIELD DOMINATED PLASMA*

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We report paired comparison observations of RF emission from two electric field dominated plasmas over the range from 1.0 MHz to 70 GHz. One of these plasmas is a classical Penning discharge configuration with a plasma length of about 80 centimeters, a diameter of about 10 centimeters, and an approximately flat axial magnetic field of up to 0.4 Tesla. The second plasma (generated in a separate apparatus) is a modified Penning discharge operated in a magnetic mirror configuration with an axial mirror ratio of 5:1, intended to simulate magnetospheric plasmas. This plasma has approximately the same dimensions as the first, and maximum magnetic fields at the mirror throats of up to 0.4 Tesla. Both plasmas are electric field dominated in the sense of having strong radial and/or axial electric fields penetrating the plasma. Both are operated steady-state in helium and argon gas, and both are enclosed in glass vacuum systems which allow RF radiation to escape the plasma without forming a resonant cavity. The instrumentation available allows a continuous spectrum of RF emission up to 1 GHz to be displayed, and measurements to be made at isolated microwave frequency bands up to 70 GHz.

At the time of writing, no information is available on the RF emission characteristics of the classical Penning discharge. The RF emissions from the modified Penning discharge have recently been found to have several interesting characteristics. In addition to the previously reported[1,2] geometric mean emission frequency, in the range from 10 to 40 MHz at background pressures below 2.4×10^{-4} Torr of Helium, we recently observed a low frequency peak, the fundamental of which is about 5 MHz, and which exhibits up to 30 or 50 harmonics before fading into the turbulent background. This peak occurs above 2.4×10^{-4} Torr, and the nonlinear mode coupling exhibited by its harmonic generation is sometimes visible up to 1 GHz. This "type II" emission appears to be related to rotating spokes driven by $E \times B/B^2$ drift, which are a consequence of the diocotron instability.

The modified Penning discharge also exhibits RF emission at frequencies above 1 GHz, including the 1 cm band at 26 GHz at which the microwave interferometer operates. The origin and nature of these high frequency emissions are a matter for continuing study.

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2C12 STABILIZATION OF THE FLUTE INSTABILITY BY A D.C. ELECTRIC FIELD IN TOROIDAL PLASMAS*

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The flute instability has been observed to be absent in the NASA-Lewis Electric Field Bumpy Torus (EFBT) and in the Elmo Bumpy Torus (EBT) at Oak Ridge. We justify these observations using the methods of classical incompressible MHD. In these experiments, radial electric fields of tens of volts per centimeter have been observed in the EBT experiment[1], and up to kilovolts per centimeter in the EFBT experiment[2]. At least in the EFBT experiment, the radial electric fields are sheared in the axial direction, and produce rapid $\bar{E}/\bar{B}$ precession about the minor perimeter. This precessional (drift) velocity is sheared with respect to distance along the z-direction of the torus. We demonstrate by means of a simple model that this shear velocity reduces the flute growth rate to such a low level that the resulting transport can have a magnitude and a scaling consistent with fluctuation-induced transport or an appropriate modification of classical diffusion.

Experimental observations of the Electric Field Bumpy Torus plasma reveal very high levels of electrostatic turbulence at all times, with a magnitude which is characteristically tens to hundreds of volts, RMS[3]. This turbulence may be driven either by thermalization of the $\bar{E}x\bar{B}/B^2$ drift velocity; or by axial shear of the drift velocity, which reverses in the vicinity of an electrode ring. This electrostatic turbulence may in some cases be accompanied by spokes rotating with the $\bar{E}x\bar{B}/B^2$ drift velocity, a manifestation of the diocotron instability characteristic of microwave magnetrons. In no case do correlation studies or spectral analysis of the electrostatic potential fluctuations of the EFBT plasma reveal gross MHD instabilities or ballooning modes characteristic of the flute or Rayleigh-Taylor instability. Indeed, the DC radial electric fields of the EFBT plasma produce a radial force much stronger than the weak centrifugal forces responsible for the flute instability, and this is probably true of EBT plasmas as well.

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9T 4 Experimental Measurement of Parallel Electric Fields in a Magnetic Mirror Plasma. J. REECE ROTH, PAUL W. HAYMAN, AND BLAIR I. FINKELSTEIN, University of Tennessee, Knoxville 37996-2100.*

We have operated a steady-state plasma in a modified Penning discharge configuration[1]. This differs from the classical Penning discharge[2] in that plasma confinement is influenced by electric fields pointing away from the plasma, and also in that the plasma operates with the anode at the midplane of an axisymmetric magnetic mirror field. The mirror ratio in these experiments was 5:1, to better simulate magnetospheric conditions. Axial profiles were measured with a high voltage floating Langmuir probe, capable of at least 5 kilovolts. The potentials observed ranged from hundreds of volts to kilovolts, and the electron kinetic temperatures were below 10 eV. Axial electric fields exceeding 100 volts/cm pointing out of the plasma were observed. Parametric variation of these electric fields will be reported.

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1Q7

LONGITUDINAL PROFILES OF ELECTROSTATIC POTENTIAL AND ELECTRON NUMBER DENSITY IN A MODIFIED PENNING DISCHARGE*

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We have operated a steady-state modified Penning discharge[1] in a magnetic mirror geometry with a ratio of maximum to minimum magnetic field of 5:1, to better simulate magnetospheric conditions. Longitudinal profiles of electrostatic potential and electron number density were taken along the axis of symmetry with a Langmuir probe under a variety of operating conditions. While these profiles were being maintained, data were also taken on the RF emissions over the range 0 to 1.0 GHz, and of the energy distribution function of ions escaping along the axis of the discharge. The voltage applied to the midplane anode ring ranged from 2 to 6 kilovolts, and the anode currents ranged from 10 to 40 milliamperes. The midplane electron number densities were about $10^8/cm^3$, and the electron kinetic temperatures were from about 5 to 20 electron volts for typical conditions. Helium gas was used in all cases, and background pressures ranged from about 10^{-4} Torr to 10^{-3} Torr.

Under conditions at the highest background pressures, the electrostatic potential profile was quite flat along the axis of the discharge, at essentially the voltage of the anode, and dropped off rapidly in the sheath next to the cold cathodes, which were located at the magnetic mirror throats. The radial potential drop between the anode ring and the axis (a radial distance of 6.3 cm) was no more than a few hundred volts. Under these conditions, one observed no significant RF emission below 1.0 GHz, and the ion energy distribution functions were monoenergetic at potentials somewhat less than the anode potential.

At low background pressures, about 10^{-4} torr, the longitudinal potential profiles were much more interesting. There was usually a radial potential drop at the midplane of about one kilovolt between the anode and the axis, implying an average radial electric field of 100-200 volts/cm. The axial potential profiles showed a longitudinal electric field of about 100-200 volts/cm, near the midplane, and away from the cathode sheath. Under the right operating conditions, the character of the axial potential profile could be adjusted from flat to monotone decreasing, to exponential, to (in a few cases) a local potential well for ions located halfway between the midplane and mirror throats. The operating conditions which resulted in strong electric fields along the axis also were highly turbulent, and tended to produce ion energy distribution functions which were spread over a range of energies. These axial electric fields represented a large and highly anomalous plasma resistivity, the mechanism of which is under investigation.

*Supported by ONR contact N00014-80-C-0063

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90 [4] Axial and Radial Profiles of Plasma Parameters in an RF-Emitting Modified Penning Discharge.* PAUL D. SPENCE and J. REECE ROTH, University of Tennessee, Knoxville, TN 37996-2100.

We have operated a steady-state modified Penning discharge in a magnetic mirror with a 5.7:1 mirror ratio, and a maximum magnetic field on the axis up to 0.4 Tesla. The electrons are trapped in an electrostatic potential well, and form two interpenetrating beams in a plasma the midplane diameter of which is about 8 cm. Recent modifications of the electrode structure have made it possible to operate at currents up to 0.5 amps at anode potentials up to 7 kilovolts. Electron number densities up to 3 x $10^{10}/cm^3$ have been observed. Under these high power conditons, RF emission was observed up to 30 dB more intense than previously reported, and at frequencies up to 1.3 GHz. Axial ion energy distribution functions were measured with a retarding potential energy analyzer, and varied from monoenergetic to Maxwellian with characteristic energies of kilovolts. Axial and radial profiles of electrostatic potential and electron number density were measured with Langmuir probes, and gave insight into the ion heating process in this discharge.

* Supported by ONR contract N00014-80-C-0063.

Spence, P. D.; and Roth, J. R.: "Axial and Radial Profiles of Plasma Parameters in an RF-Emitting Modified Penning Discharge", APS Bulletin, Vol. 28, No. 8, p. 1256 (1983).

3R3

BROADBAND RF EMISSION AND ELECTRON NUMBER DENSITY MEASUREMENTS OF AN ELECTRIC FIELD DOMINATED PLASMA*

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We have operated a steady-state modified Penning discharge [1] in a magnetic mirror geometry with a 5.7:1 mirror ratio, and a maximum magnetic field on the axis up to 0.4 Tesla. This plasma is electric field dominated, with axial electric fields which trap electrons in an electrostatic potential well, and reach values up to several hundred volts per centimeter [2]. The electron population forms two interpenetrating beams which give rise to the geometric mean and other plasma instabilities [3,4]. The midplane diameter of the plasma is about 10 cm, and it draws steady-state currents up to 0.5 amps at anode potentials up to 7 kilovolts.

Electron number densities were measured using a 27 GHz microwave interferometer, as well as axial and radial Langmuir probes. A factor of two or smaller discrepancy has been observed for localized number density measurements made by the Langmuir probes, when compared with the chord-averaged measurements from the microwave interferometer. Electron number densities up to 3 x 10^{10} electrons per cubic centimeter have been observed.

RF emissions over the frequency range from 50 to 1400 MHz have been observed in the far radiation field. The plasma emits radiation with numerous harmonics of a fundamental frequency over a broad frequency range up to at least 2.0 GHz [4]. We have used a broadband conical spiral antenna to study the spectrum of the far field radiation, as well as to make absolute net RF power emission measurements. We have used a field strength meter to calibrate our conical spiral antenna for power measnurements. Although our experiment is in a laboratory environment with RF reflections present, we have maintained far field measurement conditions and placed the antenna so that it is in an essentially homogeneous RF environment.

[1] J. R. Roth, RSI, 37, (1966) 1100-1101.
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[4] J. R. Roth, P. W. Hayman, and R. L. Pastel, A Paired Comparison of High Frequency RF Emission from Two Configurations of Electric Field Dominated Plasma, Proc. 1982 International Conf. on Plasma Physics, Goteborg, Sweden.

*Supported by ONR contract #N00014-80-C-0063.

Roth, J. R.; Rosenberg, D.; and Spence, P. D.; "Broadband RF Emission and Electron Number Density Measurements of an Electric Field Dominated Plasma", Paper 3R3, Conference Record IEEE 84CH1958-8, 1984 IEEE International Conference on Plasma Science, May 14-16, St. Louis, Missouri, p. 72, (1984).

3R4

A CALIBRATED, BROADBAND ANTENNA FOR PLASMA RF EMISSION MEASUREMENTS BELOW 1 GHz*

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A constant impedance, constant aperture antenna can make possible broadband plasma RF emission measurements which yield relative and absolute power levels. However, good technique, such as that described by Heald and Wharton [1], must be followed for the immersion of such an RF probe into plasma radiation.

We have used a complementary conical spiral antenna, similar to that described by Rumsey [2], to observe plasma RF emission over the frequency range $100 \leq \nu \leq 1200$ MHz. The RF emission was emitted by a modified Penning discharge as described by Roth [3] and Roth, Hayman, and Pastel [4]. The RF emission from the discharge typically exhibits harmonic structure over a broad frequency range, necessitating a broadband antenna with a flat frequency response curve to allow detailed spectral analysis.

The antenna consists of two metal strips of approximately uniform width wound helically on a cone made of Lexan plastic. Since the antenna is a balanced network, a balun is employed to make the transition to a 50-ohm coaxial line. The antenna feed method is critical in maintaining a uniform impedance network. Neglecting stray transmission line effects, the probe circuit for the frequency range $100 \leq \nu \leq 500$ MHz is 50 ohms due to the spectrum analyzer, paralleled by 291 ohms due to balun magnetization; the combination is fed by a 144 ohm probe aperture (see Fig. 1). Above 500 MHz, the balun seems to behave nonuniformly and requires further fine tuning to achieve a satisfactory frequency response and an accurate calibration over the frequency range from 500 MHz to 1.0 GHz. Below 100 MHz, it is not clear that the antenna remains properly immersed in the plasma radiation under present laboratory conditions.

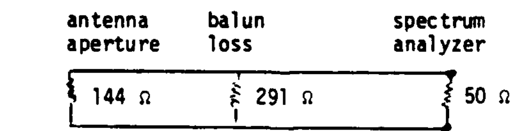

Figure 1

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4. J. R. Roth, P. W. Hayman, and R. L. Pastel, A Paired Comparison of High Frequency RF Emission from Two Configurations of Electric Field Dominated Plasma, Proc. 1982 Int. Conf. on Plasma Physics, Goteborg, Sweden.

*Supported in part by ONR Contract #N00014-80-C-0063 and in part by AFOSR contract #81-0093.

Spence, P. D.; Rosenberg, D.; and Roth, J. R.: "A Calibrated, Broadband Antenna for Plasma RF Emission Measurements Below 1 GHz, "Paper 3R4, Conference Record IEEE 84CH1958-8, 1984 IEEE International Conference on Plasma Science, May 14-16, St. Louis, Missouri, p. 73, (1984).

RF Power Scaling and Plasma Fluctuations in a Modified Penning Discharge*. PAUL D. SPENCE AND J. REECE ROTH, University of Tennessee, Knoxville, TN 37996-2100. --A modified Penning discharge (1) with a magnetic mirror ratio of 5.7:1 has been operated in the steady state with discharge currents up to 300mA. A maximum magnetic field on the axis of 0.4 Tesla is available at electron number densities up to 2×10^{10} $/cm^3$. Net broadband RF power measurements of far field radiation in the frequency range from 100 MHz to 1000 MHz have been made simultaneously with measurements of plasma electron number density and other plasma parameters. The scaling of total emitted RF power with plasma parameters has been investigated, along with the nature of electrostatic turbulence and coherent fluctutations in the plasma. Large axial and radial electric fields are believed responsible for the high level of turbulence and crossed-field instabilities which are observed (2). A secondary anode has been installed for feedback-controlled instability studies. The effect on the crossed-field diocotron instability and RF emission will be reported.

1.) J. R. Roth, RSI, 37 (1966) pp 1100-1101.
2.) J. R. Roth, P. D. Spence, L. R. Baylor, D. Rosenberg, and P. Dehkordi, Paper P1-12, 1984 Int. Conf. on Plasma Physics, Lausanne, Switzerland, June

*Supported by contract ONR N00014-80-C-0063.

Spence, P. D.; and Roth, J. R.: "RF Power Scaling and Plasma Fluctuations in a Modified Penning Discharge", paper 1W-5, APS Bulletin 29, No. 8, pp. 1197-1198, (1984).

Experimental Observation of Turbulent Energy Cascading in a Modified Penning Discharge*

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A modified Penning discharge[1] has been equipped with an effector probe located between two anode rings at the midplane of the discharge. Strong axial and radial electric fields are known to exist within the plasma[2,3] and give rise to an E x B diocotron instability. A signal at the fundamental or a harmonic of this instability is applied to the effector probe in order to "drive" the instability. Turbulent energy cascading of the low frequency (10 - 100 kHz) signal applied to the effector probe is observed both upward and downward in frequency. The excited electrostatic turbulence power spectra is as much as 20 dB above the self-excited power spectra.

The electrostatic fluctuation data are taken using capacitive probes located at various axial and radial locations. Phase and coherency spectra indicate the spontaneous formation of coherent motions with well defined group velocities. The effect of the externally applied signal is to increase the coherence and extend the linear portion of the phase spectra to higher frequencies. In some cases the applied signal causes the formation of coherent spoke-like structures with both axial and radial propagation velocities, which did not exist in the self-excited plasma. The coherence length and radial extent of some of the observed disturbances will be reported.

Electron heating is observed with the application of the externally applied effector signal. An increase in the bulk resistivity of the plasma usually occurs when the level of turbulence is increased.

The modified Penning discharge has a 5.7 to 1 mirror ratio with discharge currents of 50 to 200 mA and discharge voltages of 1 to 5 kV usually applied. Gas pressures from 10 to 100 microtorr are used with number densities from 10^8 to 10^{10} #/cm^3 observed. Electron temperatures of 10 to 100 eV are obtained.

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2) Spence, P.; and Roth, J. R.: "Axial and Radial Profiles of Plasma Parameters in an RF-Emitting Modified Penning Discharge", APS Bulletin Vol. 28 No. 8, p, 1256-1265, (1983).

3) Roth, J. R.; Spence P., Baylor, L.; Rosenberg, D.; and Dehkordi, P: "Correlation of RF Emission, Plasma Wave Propagation, and Plasma Turbulence in Classical and Modified Penning Discharges", Paper P1-12, Proceedings of the International Conference on Plasma Physics, Lausanne, Switzerland, June 27-July 3, 1984, p. 13.

*Supported by the Office of Naval Research contract ONR N 00014-80-C-0063.

Spence, P.; Laroussi, M.; Rosenberg, D.; and Roth, J. R.: "Experimental Observation of Turbulent Energy Cascading in a Modified Penning Discharge", Paper 5P-2, Conference Record, IEEE 85CH2199, 1985 IEEE International Conference on Plasma Science, June 3-5, 1985, Pittsburgh, PA, p. 83 (1985).

Edge Turbulence Enhancement and Damping Using External Low Frequency RF.* PAUL D. SPENCE, MOUNIR LAROUSSI, and J. REECE ROTH, University of Tennessee, Knoxville, TN 37996-2100.--A modified Penning discharge has been operated in the steady state with discharge currents up to 300 mA, number densities 10^{10}#/cm^3. The edge of the plasma has strong electric fields giving rise to E x B drift instabilities, and the core of the plasma is subject to ∇n drifts. These instabilities result in strong electrostatic edge turbulence with a frequency range of 1-500 kHz. An effector probe has been installed at the midplane of the discharge. A low frequency, high voltage signal is applied, and results in either enhancement or damping of the edge turbulent spectra. Enhancement by as much as 20 dB is accomplished by driving an existing ∇n or E x B instability. Increased plasma temperatures, as well as increased resistivity, are observed with turbulence enhancement. Damping of the edge turbulence is accomplished by applying an effector signal at a frequency A factor of 4 or 8 below an existing E x B or ∇n instability. The decrease in turbulence is accompanied by an increased average number density as well as electron heating.

*Supported by ONR contract N00014-80-C-0063.

Spence, P. D.; Laroussi, M.; and Roth, J. R.: "Edge Turbulence Enhancement and Damping Using External Low Frequency RF", APS Bulletin Vol. 30, No. 9 (1985) p. 1368.

Plasma Diagnostic Data Handling System Based on the VAX 11/780 and the Lecroy 3500 Signal Analyzer as a Remote Terminal.* REZA GHAYSPOOR and J. REECE ROTH, Department of Electrical Engineering, University of Tennessee, Knoxville, TN 37996-2100.--The nonlinear characteristics of data obtained by most plasma diagnostic equipment makes computer-aided data handling desirable. The objective of this work is to develop an integrated system utilizing digital spectral analysis techniques in order to understand the nature and origin of the fluctuations and their connection with fluctuation-induced transport. The approach is to digitize the data, and to generate, with the aid of a computer, various spectral properties by means of the fast fourier transform. Of particular interest is the computer generated auto-power spectrum, cross-power spectrum, phase spectrum, and transport spectrum. Software programs based on those developed by Jae Hong at the University of Texas[1] are utilized for these spectra. The Lecroy 3500-SA signal analyzer and VAX 11/780 are used as the data handling system in this work. In this report, the software aspects of linking these two systems will be described.

1. Jae T. Hong, "Development of a Plasma Fluctuation Diagnostic Based on Digital Time Series Analysis,"

*Supported by ONR Contract N00014-80-C-0063

Ghayspoor, R.; and Roth, J. R: "Plasma Diagnostic Data Handling System Based on the VAX 11/780 and the LeCroy 3500 Signal Analyzer as a Remote Terminal", APS Bulletin, Vol. 30, No. 9 (1985) p. 1419.

Scaling of Radiated RF Power for Classical and Modified Penning Discharges.* DAVID ROSENBERG, PAUL D. SPENCE, MOUNIR LAROUSSI, and J. REECE ROTH, Plasma Science Laboratory, University of Tennessee, Knoxville TN 37996-2100.--Both the modified and the classical Penning discharges have been observed to emit broadband RF radiation from 50 to 1500 MHz[1]. Using a broadband calibrated antenna,[2] net integrated RF power measurements have been made of the near- and far-field radiation in the bandwidth from 100 to 1000 MHz. The RF power scaling as a function of the number density and discharge power has been measured for the two forms of Penning discharge. Near field measurements have been made in an attempt to assess some of the effects of attenuation and scattering caused by the boundary conditions of the laboratory environment. Under conditions when the far field radiation has been observed to be predominantly linearly polarized along the static B field, a dipole-like current distribution may exist in the plasma.

1. J. R. Roth, et al., Paper P1-27a, Int. Conf. on Plasma Physics, Lausanne, 1984.
2. P. D. Spence, et al., Proc. IEEE Int. Conf. on Plasma Science, (1984), p. 73, IEEE 84CH1958-8.

*Supported by AFOSR 81-0093 and ONR N00014-80-C-0063.

Rosenberg, D.; Spence, P. D.; Laroussi, M.; and Roth, J. R.: "Scaling of Radiated RF Power for Classical and Modified Penning Discharges", APS Bulletin, Vol. 30, No. 9, (1985) p. 1551.

3C4

AN IMPROVED MHD MODEL FOR THE EARTH'S MAGNETIC FIELD*

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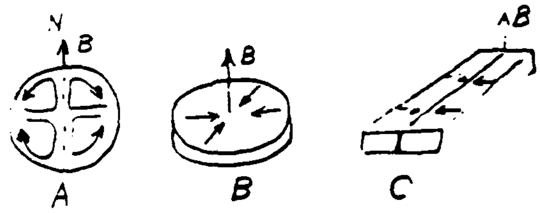
A large literature exists concerning the origin of the Earth's magnetic field via a thermally-driven MHD generator.(1) The universal opinion is that a symmetric flow pattern cannot support a steady-state field. In this paper, we demonstrate that a symmetric flow can support a steady-state magnetic field, if the electrical conductivity of the magma is allowed to vary as a function of temperature. This is equivalent to variation as a function of radius in a planetary interior.

As a first assumption, we model the Earth's core as composed of two convection cells, as shown below in A. However, the return path flows over the surface of the



planet, where the temperature and conductivity is lower. Thus, the MHD effect of the return path can be to first order neglected. Our equivalent path is shown in B. For ease of computation, a slab model is shown in C.

The differential equation governing the flow is,

$$\frac{1}{\mu_0\sigma}\frac{\partial^2 B_z}{\partial y^2} + 2v_0 B_z \delta(y) + v_0 \frac{\partial B_z}{\partial y}\,\mathrm{signum}(y) = \frac{\partial B_z}{\partial t}\ .$$

The first term is the standard diffusion term. The third term is Alfven's convection term. The second term is our new term, which corresponds to a source at the center.

The steady-state solution of this differential equation is, on the right half plane,

$$B_z = B_0 e^{-(v_0\sigma\mu_0)y} + B_1$$

which produces a steady-state narrow peak on axis. Use of known values of the core conductivity and flow rate produce a peak for B having a half-width about 10 km broad.

(1) For example, H.K. Moffatt, "Magnetic Field Generation in Electrically Conducting Fluids", Cambridge University Press, 1978.

*Work supported by the Air Force Office of Scientific Research under grant AF-AFOSR-82-0045 (Alexeff) and office of Naval Research contract ONR N00014-80-C-0063 (Roth). (A preliminary version of this work was presented at this conf---nce last year).

Igor Alexeff and J. Reece Roth, "An Improved MHD Model for the Earth's Magnetic Field", Paper 3C4, Proceedings of the 1986 International Conference on Plasma Science, May 19-21, 1986, Saskatoon, Canada IEEE Catalog No. 86CH2317-6, (1986) p. 48.

4P14

Effective Collision Frequency Measurements on a Weakly Ionized Turbulent Plasma*

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Effective collision frequencies have been measured using resonant absorbtion of an extraordinary wave propagating across a plasma column. Both the attenuation and phase shift of a transmitted wave are measured in a swept frequency measurement using an HP 8510 Network Analyzer. The measured attenuation and phase shift at and near a resonant frequency are compared to a numerical solution of the Appleton equation[1] using relevant plasma parameters.

The width at twice the minimum transmitted power at resonance is taken to be an "effective" collision frequency. This definition agrees with the solution of a forced-damped harmonic oscillator and numerical solutions of the Appleton equation.

The steady state plasma column used for the experiment is generated by a classical Penning discharge. Electron number densities of 1×10^9 to 5×10^{10} #/cm^3 are obtained with electron temperatures typically 10 eV. The plasma is typically only ~ 1% ionized so that electron-neutral collisions would normally dominate.

The collision frequencies measured are 2 to 20 times electron-neutral collision frequencies computed using tabulated cross secitons.[2] A strong dependence on the static magnetic field is observed. The effective collision frequency increases with static magnetic field. These anomalous collision frequencies are believed to be related to the high level of electrostatic turbulence associated with the discharge.[3]

1. Heald M. A. and C. B. Wharton, Plasma Diagnostics with Microwaves, Krieger 1978 p. 26.
2. Brown, Sanborn C., Basic Data of Plasma Physics, MIT Press (1967) p. 17.
3. M. Laroussi, P. Spence, D. Rosenberg, J. C. Mannone and J. R. Roth, "RF Emission Power and Its Dependence on Plasma Parameters and Turbulence in a Classical Penning Discharge", Paper SP-3, 1985 IEEE International Conference on Plasma Science, Pittsburgh, PA.

*This paper was supported by the Office of Naval Research contract ONR N00014-80-C-0063.

Paul Spence and J. Reece Roth, "Effective Collision Frequency Measurements on a Weakly Ionized Turbulent Plasma", Paper 4P14 Proceedings of the 1986 International Conference on Plasma Science, May 19-21, 1986, Saskatoon, Canada IEEE Catalog No. 86 CH2317-6 (1986) p. 75.

5P9

A Three-Channel Plasma Diagnostic Data Handling System Based on the VAX 11/780 and the LeCroy 3500 Signal Analyzer*

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Due to nonlinear characteristics of data obtained by most plasma diagnostic systems and considering the time required for processing these data, computers are an important element of the data handling system in plasma labs. The objective of this work is to develop an integrated data acquisition and handling system based on digital time series analysis techniques. These techniques will enable us to understand the nature and origin of the plasma fluctuations and their connections to the fluctuation-induced transport rate. The approach is to digitize the data, and to generate various spectra by means of Fast Fourier Transforms (FFT). Of particular interest is the computer generated auto-power spectrum, cross-power spectrum, phase spectrum (Channel 1 vs. Channel 2, and Channel 1 vs. Channel 3), squared coherency spectrum (Channel 1 vs. Channel 2, and Channel 1 vs. Channel 3), and transport spectra. Software programs based on those developed by Jae. Y. Hong[1] at the University of Texas are utilized for these spectra. In this work, the potential fluctuations are measured by two capacitive probes (Channel 1 and 2) separated by a known angle at the same radius. Channel 3 measures ion density fluctuations with a Langmuir probe. This paper is an updating of the paper presented at the 11th Symposium on Fusion Engineering at Austin, TX.[2]

*This work was supported by the Office of Naval Research under Contract ONR N-00014-80-C-0063.

1. Jae Y. Hong. "Development of a Plasma Fluctuation Diagnostic Based on Digital Time Series Analysis," (Master's Thesis), the University of Texas at Austin, May 1979.
2. Reza Ghayspoor and J. Reece Roth, "Plasma Diagnostics Data Handling System Based on the VAX 11/780 and the LeCroy 3500 Signal Analyzer as a Remote Terminal." Paper 5P47 presented at the 11th Symposium on Fusion Engineering, November 18-22, 1985, Austin, Texas.

Reza Ghayspoor and J. Reece Roth, "A Three-Channel Plasma Diagnostic Data Handling System Based on the VAX 11/780 and the LeCroy 3500 Signal Analyzer", Paper 5P9, Proceedings of the 1986 International Conference on Plasma Science, May 19-21, 1986, Saskatoon, Canada, IEEE Catalog No. 86 CH2317-6 (1986) p. 96.

Effective Collision Frequency Measurements on a Weakly Ionized Plasma*, PAUL SPENCE, J. REECE ROTH, University of Tennessee, Knoxville, TN 37996-2100 -- Effective collision frequencies for electrons have been measured using cyclotron resonant absorbtion of a microwave beam in the extraordinary mode. The microwave beam is propogated across a uniform steady state plasma column, with the attenuation and phase shift of the transmitted beam being made by a Hewlett Packard 8510 Network Analyzer. The phase and attenuation measurements are compared with numerical solutions of the Appleton equation using relevant plasma parameters.

The collision frequencies measured are 2 to 20 times electron-neutral collision frequencies computed using tabulated cross sections[2] A strong dependence on the background turbulence level is observed. Measured collision frequencies are compared to a theoretical result by Galeev and Sagdeev[3], for an effective collision frequency due to turbulence.

1. Heald M. A. and C. B. Wharton, Plasma Diagnostics with Microwaves, Krieger 1978, p. 26.
2. Brown, Sanborn C., Basic Data of Plasma Physics, MIT Press 1967.
3. Rosenbluth M. N., Sagdeev R. Z. gen. editors; Basic Plasma Physics II, North-Holland Pub. 1984.

*Supported by ONR contract #N00014-800-C-0063

Spence, P. and Roth, J. R.: "Effective Collision Frequency Measurements on a Weakly Ionized Plasma" APS Bulletin, Vol;. 31, No. 9, p. 1576 (1986).

Collision Frequency Measurements on a Turbulent Plasma*

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Abstract

Effective collision frequencies have been measured on a turbulent plasma by electron cyclotron resonance absorbtion. The absorbtion measurements are interpreted in terms of numerical solutions of the Appleton equaton [1] to yield an effective collision frequency equal to the full width of the absorbtion curve at twice the resonance minimum. The scaling of this effective collision frequency to the background drift turbulence is measured and compared to an effective collision frequency due to Langmuir turbulence derived by "Galeev and Sagdeev [2]. Drift wave energy for scaling is based on the form described by Horton [2]. Using feedback or a coherent source, a signal is applied to the plasma to directly enhance or damp the turbulent spectra. Broadening of the absorbtion curve is observed under turbulence enhancement. Care is taken to monitor the electron kinetic temperature in order to account for a velocity dependent collision frequency.[3]

The plasma discharge used for these studies is a uniform Penning discharge capable of electron number densities of up to a few $10^{10}/cm^3$, at electron temperatures of 10 to 100 eV. The 100 cm long discharge consists of an anode cylinder and two cathode plates. The 35 cm anode cylinder has a tungsten wire running parallel to the axis 1 cm from the inside surface. The high voltage signal for turbulence enhancement or damping is applied to the effector wire.

[1] Heald, M. A. and Wharton, C. B. (1978) Plasma Diagnostics with Microwaves, Krieger, p. 26.
[2] Rosenbluth, M. N. and Sageleev, R. Z.; gen editors (1984) Basic Plasma Physics II, North-Holland Pub.
[3] Shkarofsky, I. P. (1961) Values of the transport coefficients in a plasma for any degree of ionization. Can J. Phys 39, 1619.
*Supported by Office of Naval Research Contract ONR N00014-80-C-0063.

Spence, P. and Roth, J. R.: "Collision Frequency Measurement on a Turbulent Plasma", Paper 3B9 Proceedings of the 1987 IEEE International Conference on Plasma Science, June 1-3, 1987, Arlington, VA, IEEE Catalog No. 87CH2451-3 (1987) p. 48.

THEORY OF PLASMA ION IMPLANTATION FOR HARDENING METALS*

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ABSTRACT

A problem with existing methods of hardening metals by ion implantation is that the ion beams normally used do not lend themselves to implanting the ions uniformly on complex surfaces such as gear teeth, screw threads, turbine blades, etc. If one inserts a metallic sample into a plasma and biases it negatively, deep into the ion saturation region as though it were a Langmuir probe, the surface of the sample will be isotropically bombarded by ions over scale sizes larger than the local Debye length. If the sample is biased to negative potentials of 50 kV or more, useful amounts of ion implantation can occur in very short times in samples such as spheres and gear teeth[1,2]. Ion energies of about 50 keV normally lead to implantation depths of a tenth of a micron or so at room temperature, but it seems that ions implanted at these energies manage to migrate ahead of the wear surface and maintain surface hardness even after several tenths of a micron of surface material are worn away[2].

This paper examines the plasma parameters required to achieve a given level of ion implantation in complex metal objects, how to calculate exposure times, energy requirements, and other commercially significant factors in the application of this new process. It is shown that the surface fluxes of 50 keV ions from plasma ion implantation can exceed those from space charge limited ion beam sources; that relatively modest and easily generated steady-state plasmas can isotropically bombard samples with a Debye length and scale size of less than 0.5 mm; that an exposure time of only a few seconds is required to produce useful levels of ion implantation; that the power delivered to the sample can be made much smaller than the level required to melt it; that by pulsing the high negative biasing voltage on and off with an appropriate duty cycle, the ions required for implantation on a sample of several tens of square centimeters will not significantly deplete a relatively modest plasma; and that the total power and energy required to achieve a given level of hardness by plasma ion implantation is far below that required by conventional foundry techniques.

1. J. Bell, R. Herman, and C. Sutton, New Scientist, March 6, 1986, pp. 34-36.
2. Private communication, Dr. John R. Conrad, Univ. of Wisconsin, August, 1986.

*Supported in part by ONR contract N00014-80-C-0063 and by contract AFOSR 86-0100 (Roth).

Roth, J. R.: "Theory of Plasma Ion Implantation for Hardening Metals", Paper 6Y6, Proceedings of the 1987 IEEE International Conference on Plasma Science, June 1-3, 1987, Alington, VA, IEEE Catalog #87CH2451-3 (1987) pp. 123-24.

Edge Turbulence Dynamics with External Forcing*. P. D. SPENCE AND J. REECE ROTH, UTK Plasma Science Laboratory, University of Tennessee, Knoxville 37996-2100. -- The edge region of a magnetically confined plasma is characterized by various drift waves and broadband edge turbulence. Previous studies[1] have shown that the edge turbulence in a low density steady state Penning discharge could be enhanced or under certain conditions damped by the use of a coherent effector signal. The presence of a turbulently enhanced collision frequency for electrons has subsequently been measured.[2] The effective collision frequency appears to scale as the square of the fluctuating potential (ϕ) for the edge turbulence. When viewed in phase space ($\dot{\phi}$ vs ϕ), characteristic behavior is observed in the limit cycles for damping or enhancement of the turbulence. This behavior is currently being studied in order to determine the key physical parameters that can be controled in order to induce turbulent damping an enhancement under arbitrary conditions.

*Work supported by Office of Naval Research Contract ONR N00014-80-C-0063

1. P. Spence, M. Laroussi, J. R. Roth, APS Bulletin, vol. 30, No. 9 (1985) p. 1368
2. P. Spence, J. R. Roth, Proc. IEEE International Conf. or Plasma Science, Cat. No. 87CH2451-3, (1987) p. 48.

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1P1

Electron Collison Frequency Enhancement and Resistive Drift Wave Turbulence*

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Previous studies[1] of a turbulently enhanced electron collision frequency have shown scaling consistent with the formula[2]:

$$\nu_{eff} = \omega_{pe} \frac{W}{n T_e}$$

where W is the wave energy density of turbulent waves on the order of a Debye length. Using capacitive probes and microwave scattering, a turbulent power spectrum was measured and related to the electron collision frequency determined by electron cyclotron resonance broadening. The turbulent power measured was assumed to be linearly proportional to the wave energy density W.

Capacitive probes and a two channel microwave scattering system have now been calibrated in an attempt to quantitatively measure W. The results of these measurements and details of the measurement procedure are to be reported.

The resistive drift instability is also reconsidered, with the addition of a turbulent collision frequency. The linear growth rate of these waves[3] is proportional to the electron-ion collision frequency. Since resistive drift waves often behave as source functions in a turbulent plasma, they can affect the level of turbulence in the dissipative region of the spectrum which in turn changes the effective collision frequency. For drift waves, $\nu_{eff} \propto \tilde{\Phi}^2$, where $\tilde{\Phi}$ is the fluctuating potential. The resistive drift instability is currently being studied incorporating this effective collision frequency.

1. P. Spence, J. R. Roth, Proc. IEEE Conf. on Plasma Science, Cat. No. 87CH2451-3, (1987) p. 48.

2. Galeev A. A. and R. Z. Sagdeev, in: Reviews of Plasma Physics, ed. M. A. Leontovich (consultants Bureau, New York 1965) Vol. 7 p.147

3. Miyamoto K. (1980) Plasma Physics for Nuclear Fusion p. 303, MIT press.

*Supported in part by ONR Contract N00014-88-K-0174

Spence, P. D; Stafford, S.; and Roth, J. R.: "Electron Collison Frequency Enhancement and Resistive Drift Wave Turbulence", Paper 1P1, Proceedings of the 1988 IEEE International Conference on Plasma Science, June 6-8, 1988, Seattle, WA, IEEE Catalog No. 88CH2559-3 (1988) p. 36.

1P3

THE DIVERGENCE TERM OF THE CONTINUITY EQUATIONS FOR PARTIALLY IONIZED PLASMAS WITH LONG MEAN FREE PATHS*

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At neutral gas pressures of 0.01 Torr and above, the mean free path of electrons and neutrals is much smaller than the plasma dimensions or the characteristic dimension of the density gradients in partially ionized plasmas. Under such conditions, Fick's law of diffusion is valid, and the divergence terms of the neutral and charged particle continuity equations may be written

$$-\nabla \cdot \bar{\phi} = D\nabla^2 n \tag{1}$$

for an unmagnetized plasma.

When the neutral gas pressure is below 0.01 Torr, the mean free paths of the electrons and/or neutrals can become comparable to the plasma dimensions and to the characteristic dimension of the density gradients. In such plasmas, the requirement that the mean free path be smaller than the characteristic dimension of the density gradient is no longer met, and Fick's law of diffusion is no longer valid. In this long mean free path limit, the divergence terms of the particle continuity equations must be regarded as the net particle flux across the surface of a sphere centered at the point of interest. The outward flux across this sphere depends on the particle number density within his sphere at the time of observation; the inward flux, because of the long mean free paths, depends instead on the particle number density one mean free time in the past, at a distance from the point of interest of one mean free path. This dependence of the net flux across a small sphere on the mean free time between collisions introduces a time delay. It will be shown that this time delay gives an expression for the divergence terms of the particle continuity equations, in the long mean free path limit, of

$$-\nabla_Z \cdot \bar{\phi}_n = n(Z,t)\,\bar{n}_e <\sigma v>_{ne} \tag{2}$$

for the neutral gas equation, and

$$-\nabla_Z \cdot \bar{\phi}_e = \bar{n} <\sigma v>_{ne} n_e (Z,t) \tag{3}$$

for the equation of continuity for electrons, where the bar over the number density represents a time and space average.

*Supported in part by contract ONR N00014-88K-0174 (Roth).

Roth, J. R.: "The Divergence Term of the Continuity Equations for Partially Ionized Plasmas with Long Mean Free Paths", Paper 1P3, Proceedings of the 1988 IEEE Internatonal Conference on Plasma Science, June 6-8, 1988, Seattle, WA, IEEE Catalog No. 88CH2559-3 (1988) pp. 36-37.

Investigation of the Nonlinear Behavior of a Weakly-Ionized Plasma.* S. STAFFORD, and J.R. ROTH, University of Tennessee -- Previous experiments on our classical Penning discharge have shown the existence of what appears to be a resistive drift instability.[1] By using a long, cylindrical anode and also applying RF power, relatively coherent modes have been observed. The nonlinear dynamics of these modes are to be studied. Capacitive probes are used to measure potential fluctuations. These signals are digitized and then processed with software obtained from Dynamical Systems Inc. This software will reconstruct the phase portraits, take Poincare sections, compute dimensions, and compute Lyapunov exponents. The goals of this work are to obtain coherent modes and then study the effects of varying the plasma parameters, and to determine whether low dimensional chaos is occuring.

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* Supported in part by ONR Contract N00014-88-K-0174

1. P. Spence, S. Stafford, and J.R. Roth, Proc. IEEE Conference on Plasma Science, IEEE Cat. no. 88CH2559-3, (1988) p. 36

Stafford, S; and Roth, J. R.: "Investigation of the Nonlinear Behavior of a Weakly Ionized Plasma", APS Bulletin, Vol. 33, No. 9 (1988) p. 2016.

5P12 COMPUTER-AIDED REDUCTION OF PLASMA DATA

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Electrical Engineering Department
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Poor signal-to-noise ratios and the non-linear characteristics of the data obtained by most plasma diagnostic equipment makes computer-aided data handling a desirable feature in plasma laboratories. The Lecroy 3500-SA32 signal analyzer is used as the data handling system in this work. The performance of the Lecroy 3500-SA32 signal analyzer, used for recording and reducing the plasma data under the noisy environment of the laboratory, is reported.

The data characteristics and software programs are discussed for three types of plasma diagnostic equipment: 1) Langmuir Probes; 2) Charge Exchange Neutral Energy Analyzers; 3) Retarding Potential Energy Analyzers. The experimental data are taken from the modified Penning discharge plasma ($10^9 < n_e < 10^{11}/cm^3$, $T_e < 200$ ev). In order to protect the computer internal circuitry and to have satisfactory data acquisition and handling, methods for dealing with the noisy environment, including stray magnetic fields, RF radiation, and transient spikes on power lines, are also developed.

Three computer programs are included which obtain an iterated best fit of experimental data to the corresponding analytical expressions for each case. Plasma parameters such as ion kinetic temperature, electron kinetic temperature, electron number density, plasma potential, etc. are available on a real-time basis. Computer programs can be run on the Lecroy 3500-SA computer*. The new data handling system enalbes the user to do a real-time analysis of data by using the interactive features of the Lecroy 3500-SA32 system.

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*In the case of retarding potential analyzer a computer porgram written by Loretta R. Ellis was modified.

Shariati, S: "Computer-Aided Reduction of Plasma Data", Paper 5P12, Proceedings of the 1984 IEEE International Conference on Plasma Science, May 14-16, 1984, St. Louis, MO, IEEE Catalog No. 84CH 1958-8 (1984) p. 117.

1W10 Growing Waves and Electromagnetic Emission from Two Oppositely Directed Electron Beams in a Cold Background Plasma.* --J. REECE ROTH AND IGOR ALEXEFF, University of Tennesee, Knoxville, TN 37996-2100.--We present a generalization of previous theoretical work (1) to the case of two non-relativistic, oppositely directed interpenetrating electron beams of unequal density interacting with a cold background plasma. These conditions can be reduced to a sixth-order cold plasma dispersion relation, which has growing and damped solutions. In the case of two beams, each 1/2 of the total electron density, interacting with cold ions, we recover our previous result (1); growing waves near the geometric mean of the electron and ion plasma frequency. When the beams are much less dense than the cold electron background density, the growing waves are near the electron plasma frequency of the cold electron population. The maximum growth rates are not at the beam electron plasma frequency or at the upper or lower hybrid frequency. The frequency of an oscillator based on this instability can be tuned by adjusting the relative intensity of the two beams as well as the beam density relative to the background plasma.

1.) I. Alexeff, J. R. Roth, J. D. Birdwell, and R. Mallavarpu, Physics of Fluids, 24 (1981) pp1348-57.

*Supported in part by AFOSR contracts 81-0093 and 82-0045, and by ONR contract N00014-80-C-0063.

Roth, J. R.; and Alexeff, I: "Growing Waves and Electrostatic Emission from Two Oppositely Directed Electron Beams in a Cold Background Plasma", APS Bulletin, Vol. 29, No. 8 (1984) p. 1198

Investigation of the Nonlinear Behavior of a Weakly-Ionized Plasma*

Scott Stafford and J. Reece Roth

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Department of Electrical and Computer Engineering
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Knoxville, Tennessee 37996-2100

Stafford, S.; and Roth, J. R.: "Investigation of the Nonlinear Behavior of a Weakly-Ionized Plasma" Conference Record, 1989 IEEE International Conference on Plasma Science, May 22-24, 1989, Buffalo, NY

The nonlinear behavior of plasma has been studied by conventional means, such as auto power spectral analysis and correlation studies, for many years. Since the arrival of chaotic dynamics in the early 1960's, many new methods of analyzing turbulence have been developed. In recent years these methods have been applied to research on plasma fluctuations. Thus far, most applications have been to pulsed or unmagnetized plasmas. This paper will describe recent progress on the application of chaos theory to a steady-state magnetized plasma.[1]

This research was conducted on a classical Penning discharge, which is inherently turbulent. This rules out the possibility of observing a transition from coherency to turbulence. However, by choosing appropriate boundary conditions, it was possible to produce relatively coherent modes. This was achieved by using a long cylindrical anode and a coaxial cathode. This arrangement creates a constant radial electric field along the axis, which in turn causes an E x B instability to develop in the edge region of the plasma. These modes can be damped or enhanced by varying the plasma parameters. Turbulence data were obtained by using a capacitive probe to measure the potential fluctuations. The signals were digitized and recorded with a LeCroy data acquisition system interfaced to an IBM AT computer.

In order to study the nonlinear behavior of the fluctuations, a software package was obtained from Dynamical Systems, Inc. The package consists of routines that plot in two or three dimensions, calculate Fourier spectra, reconstruct phase portraits, take Poincare sections, compute correlation dimensions, compute Lyapunov exponents, and perform various other data manipulations.

Our principal goal was to look for evidence of low dimensional chaos. Another was to look for a trend, or lack of trend, that related the state of turbulence to the plasma parameters. The study was conducted for three different plasma cases. In each case a different parameter was varied. Those parameters included the anode voltage, background pressure, and magnetic field strength.

1. Stafford, S.; and Roth, J. R.: APS Bulletin, Vol. 33, No. 9 (1988) p. 2016.

*Supported by Contract ONR N00014-88-K-0174.

APPENDIX H

Title Pages and Abstracts of
Graduate Theses Completed with
The Support of ONR Contracts
N00014-80-C-0063 and 88-K-0174

COMPUTER-AIDED REDUCTION OF PLASMA DATA

A Thesis

Presented for the

Master of Engineering

Degree

The University of Tennessee, Knoxville

Saeid Shariati

March 1985

ACKNOWLEDGEMENTS

The autnor wishes to acknowledge with appreciation to his major professor, Dr. J. R. Roth, for his encouragement, help, patience, and advice during the course of this research. The members of his committee were very helpful with their valuable suggestions and the review of the thesis.

A special thanks is due to Dr. Walter L. Green for his valuable help and encouragement during 1979 and 1984.

Finally, the author wants to extend his appreciation to his parents and his wife, Cynthia, for their support and encouragement.

The research was funded by the Office of Naval Research Contract ONR-N00014-80-C-0063.

ABSTRACT

Poor signal-to-noise ratios and the nonlinear characteristics of the data obtained by most plasma diagnostic equipment makes computer-aided data handling a desirable feature in plasma laboratories. The Lecroy 3500-SA32 signal analyzer is used as the data handling system in this work. The performance of the Lecroy 3500-SA32 signal analyzer, used for recording and reducing plasma data under the noisy environment of the laboratory, is reported. The data characteristics and software programs are discussed for three types of plasma diagnostic equipment: (1) Langmuir Probes; (2) Charge Exchange Neutral Energy Analyzers; (3) Retarding Potential Energy Analyzers. Three computer programs in FORTRAN 80 are included which obtain an iterated best fit of experimental data to the corresponding analytical expressions for each case. Plasma parameters such as ion kinetic temperature, electron kinetic temperature, electron number density, plasma potential, etc. are available on a real-time basis.

TABLE OF CONTENTS

VITA

The author was born in Tehran, Iran, on December 21, 1957. He attended primary school from August 1963 to June 1969 and high school from August 1969 to June 1975.

He started his university work in August 1975 at the Arya-Mehr University of Technology in the Physics Department, and in September 1978 he came to the United States to continue his education.

He has been attending The University of Tennessee, Knoxville in the Electrical Engineering Department since April 1979. He received the degree of Bachelor of Science in Electrical Engineering in March 1981.

He began his studies for the Master of Engineering degree in the Electrical Engineering Department with a teaching assistantship in April 1981.

He was an instructor of physics and computer science at Knoxville College from September 1982 to June 1983. He received a research assistantship (funded by the Office of Naval Research) in the UTK Plasma Science Laboratory in September 1983, where he did his thesis research.

DEVELOPMENT OF AN INTEGRATED DATA ACQUISITION AND HANDLING SYSTEM BASED ON DIGITAL TIME SERIES ANALYSIS FOR THE MEASUREMENT OF PLASMA FLUCTUATIONS

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Reza Ghayspoor

December 1985

ACKNOWLEDGEMENTS

The author wishes to express his sincere appreciation to his major professor, Dr. J. R. Roth, for his encouragement, patience, and helpful advice throughout the course of this research.

Special thanks go to Dr. Igor Alexeff, and Dr. D. W. Bouldin, the members of his committee, for review of the thesis.

Appreciation is also extended to Ms. Roberta L. Campbell for typing the manuscript of the thesis.

Finally, the author wishes to express his appreciation to his parents for their support and encouragement throughout his academic career.

This work was supported by the Office of Naval Research under Contract ONR N-00014-80-C-0063.

ABSTRACT

The nonlinear characteristics of data obtained by many plasma diagnostic systems requires the power of modern computers for on-line data processing and reduction. The objective of this work is to develop an integrated data acquisition and handling system based on digital time series analysis techniques. These techniques make it possible to investigate the nature of plasma fluctuations and the physical processes which give rise to them. The approach is to digitize the data, and to generate various spectra by means of Fast Fourier Transforms (FFT). Of particular interest is the computer generated auto-power spectrum, cross-power spectrum, phase spectrum, and squared coherency spectrum. Software programs based on those developed by Jae. Y. Hong at the University of Texas are utilized for these spectra. The LeCroy 3500-SA signal analyzer and VAX 11/780 are used as the data handling and reduction system in this work. In this report, the software required to link these two systems will be described.

TABLE OF CONTENTS

VITA

The author was born in Mashad, Iran, on January 21, 1952. He attended elementary school from September 1959 to June 1965 and high school from September 1965 to June 1971. He was admitted to the Institute of Technology of Mashad in August 1972 and obtained his Associate Degree in Mechanical Engineering in June 1974.

In the summer of 1978 he was admitted to the University of Tennessee, Martin in the Electrical Engineering Department. After one year at that University, he transferred to the University of Tennessee, Knoxville where he received the degree of Bachelor of Science with honors in Eletrical Engineering in March, 1982.

He began his studies for the Master of Science in the Electrical Engineering Department in September 1982. He held a teaching assistantship in September of 1983, and a research assistantship (funded by the Office of Naval Research) in the UTK Plasma Science Laboratory in September 1984, where he did his thesis research.

The author received his M.S. in Electrical Engineering in December 1985.

Investigation of nonlinear behavior in a weakly-ionized plasma

Master of Science Thesis Proposal

Scott A. Stafford

December 4, 1987

Investigation of the Nonlinear Behavior of a Weakly-Ionized Plasma.* S. STAFFORD, and J.R. ROTH, University of Tennessee -- Previous experiments on our classical Penning discharge have shown the existence of what appears to be a resistive drift instability.[1] By using a long, cylindrical anode and also applying RF power, relatively coherent modes have been observed. The nonlinear dynamics of these modes are to be studied. Capacitive probes are used to measure potential fluctuations. These signals are digitized and then processed with software obtained from Dynamical Systems Inc. This software will reconstruct the phase portraits, take Poincare sections, compute dimensions, and compute Lyapunov exponents. The goals of this work are to obtain coherent modes and then study the effects of varying the plasma parameters, and to determine whether low dimensional chaos is occuring.

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* Supported in part by ONR Contract N00014-88-K-0174

1. P. Spence, S. Stafford, and J.R. Roth, Proc. IEEE Conference on Plasma Science, IEEE Cat. no. 88CH2559-3, (1988) p. 36

OUTLINE

Ph.D. Thesis

Paul Daniel Spence

June, 1989

Introduction

The following paper is intended to update the doctoral committee of Paul Spence on current research in the UTK plasma lab and present an outline for dissertation research. Although specific goals of the dissertation research are not set, the scope and intent should be clear. The title; "Edge Turbulence Dynamics and Effective Collision Frequency Measurements", may be appropriate, however. As the research topic is multi-faceted, it is understood that additional study is required to clarify the specifics of the dissertation.

This paper consists of four main parts. Part I is a review of the experimental apparatus used in the UTK Plasma Lab and presents the type of data that have been studied. The concept of an "effective" collision frequency and its measurement for electrons is discussed in part I.

Part II deals with some of the pecularities of drift wave turbulence and presents possible mechanisms for the damping or enhancement of such turbulence. The distinction between a parametric process and a forced oscillation is made. Some recent results using bifurcation theory are discussed.

Part III details the experimental modifications currently underway and expands on the theoretical and numerical tools available for this research.

Part IV is a discussion of the general concept of nonlinear dissipation in connection with the work outlined in part III.

Outline

I. UTK Plasma Lab: Hardware and Results

1. Experimental Apparatus
2. Diagnostic Tools
3. Edge Turbulence Enhancement and Damping
4. Collision Frequency Measurements and Scaling

II. Review of Literature

1. Drift Wave Turbulence
2. Drift Vorticies
3. Parametric Process
4. Nonlinear Oscillations
5. Routes to Turbulence: Bifurcation Theory

III. Future Research

1. Experimental
2. Theoretical
3. Numerical

IV. Dissertation Objectives: A Discussion

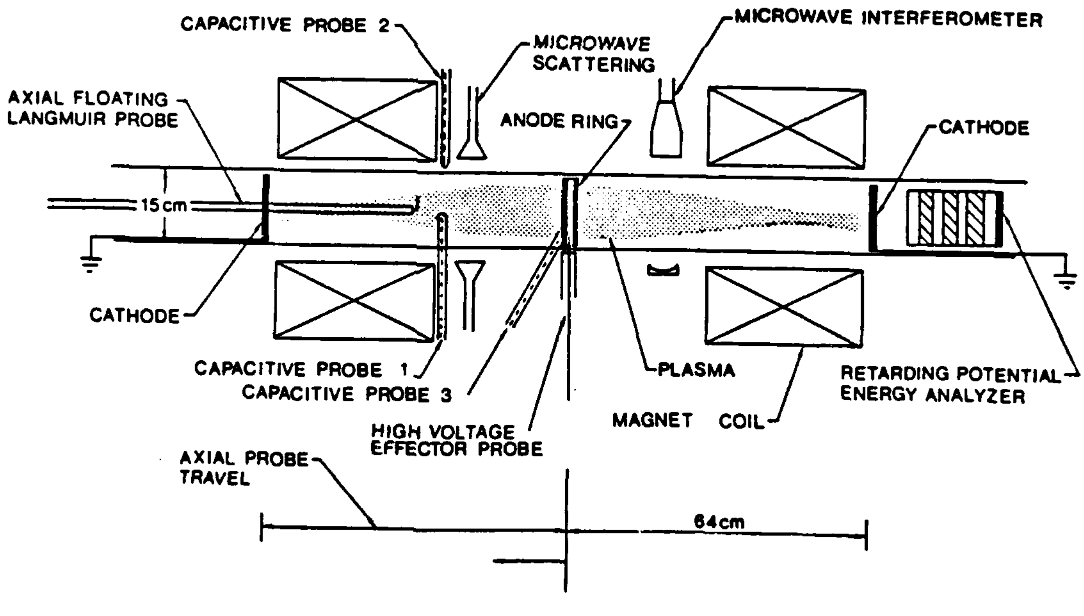
V. Symbols

VI. Appendices

VII. References

I. Background

The UTK Plasma Lab operates a steady state modified Penning discharge capable of electron number densities of up to a few $10^{10}/cm^3$, at electron temperatures of 10 to 100 eV. The 60 cm long discharge consists of an anode ring and two cathode end plates (see Fig. 1). The confinng magnetic field has a 5.1 to 1 mirror ratio with the maximum field variable up to 0.33 tesla. A glass vacuum vessel surrounds the discharge and allows external detection of the electrostatic fluctuations associated with the turbulence and drift waves on the edge of the plasma. The base pressure of the system is typically 6 microtorr, with operating pressures of 50 to 200 microtorr.



MODIFIED PENNING DISCHAGE

(TOP VIEW)

Figure 1

At the midplane of the discharge a tungsten probe is inserted radially thru the anode ring. This "effector probe" is D.C. biased to the anode potential and is A.C. coupled to either a full sine wave or a positive half rectified sine wave. A Ling power amplifier capable of up to 1.0 amp at 5 kilovolts over the frequency range 0.5 to 100 kHz is used to drive the effector probe for turbulence enhancement and damping studies.

Electrostatic fluctuations of the plasma edge are detected using capacitive probes located on the glass vacuum vessel. Detected signals in the frequency range 0.01 to 2 MHz are amplified, filtered and viewed on a spectrum analyzer, microwave network analyzer, or digitally sampled using a LeCroy 3500 signal processing system. Under conditions having a high degree of coherence the microwave network analyzer yields the phase information between two probes. This phase information can be related to the direction and velocities of wave propagation. Digital time series analysis of the transient samples of these signals is also performed to yield auto and cross power spectra, phase and coherency spectra, as well as the bispectrum and squared bicoherency.

Experimental Data

The edge region of a magnetically confined hot plasma is characterized by large temperature and density gradients. These gradients act as energy reservoirs for various nonlinear instabilities resulting in drift waves and broadband edge turbulence. Drift waves in a turbulent plasma are typically quasiperiodic with finite coherence lengths. When externally enhanced these waves can have increased

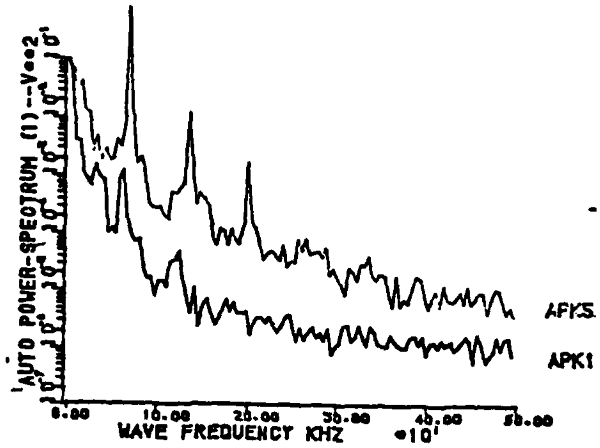
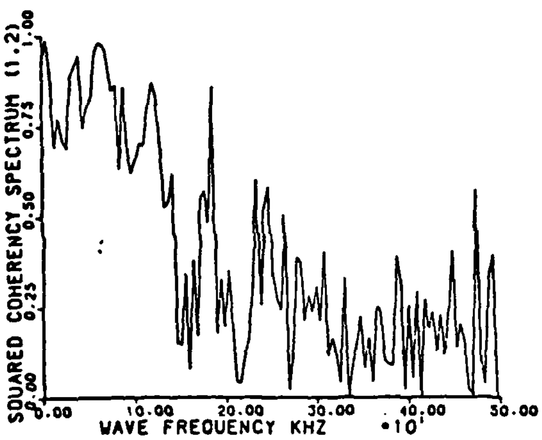


fig. 2



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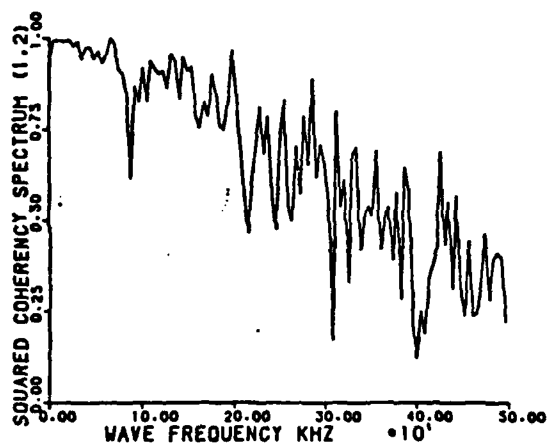
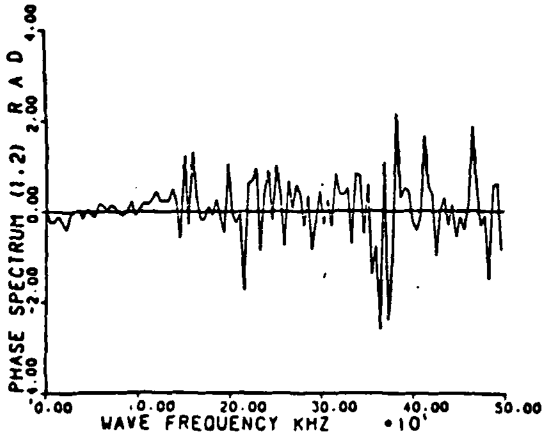


fig. 4



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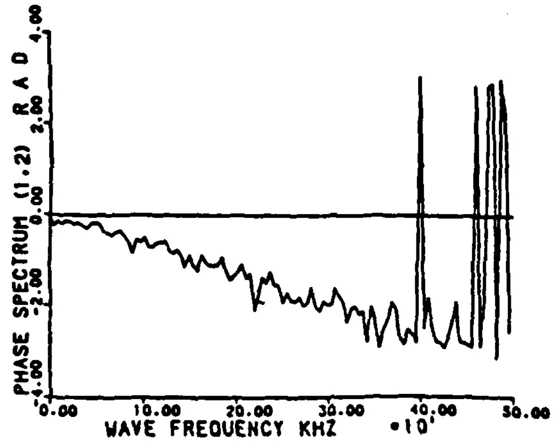


fig. 6

coherence lengths and exhibit strong mode coupling, with the number of observed harmonics doubling. Increased background turbulence, electron heating and modification of the spectral index are observed. Under special conditions using a subharmonic external signal, drift modes and background turbulence have been damped. Increased electron temperature and number density are observed with damping.

Auto power spectra for typical plasma conditions with and without external excitation are shown in Figure 2. The self excited spectrum (APK1) was taken on probe 1 with an anode voltage of 4400 volts and current of 38 mA. The enhanced spectrum is taken while a 68 kHz, 1 kV, 5 mA_{peak} half wave rectified signal is applied to the effector probe. The enhanced spectrum is as much as 20 dB above the self excited level. Highly nonlinear mode coupling is exhbited here due to the continuous "filling" of the spectrum. Note that energy is cascading both upward and downward in frequency space.

Figure 3 thru 6 show the phase and coherence spectra for the spectrum shown in Figure 2, and for a similar spectrum for signals taken by a second probe located azimuthally 60° from probe 1. For the enhanced turbulence, Figures 4 and 6 show increased coherency and a linear phase spectrum, yielding a well defined group velocity of approx. 5.5×10^4 m/sec. The high level of coherency in Figure 4 is a requirement for a meaningful phase spectrum. The apparent spikes on Figure 6 are due to the software programs inability to distinguish between ± 180°, with some finite noise level causing between te spectrum to flip back and forth.

Figure 7 and 8 show the effect of using a low frequency (3.4 KHz, 4 kV_{pp}, 5 mA full sine wave) to damp a high frequency mode. Electron heating and increased number density were observed with damping.

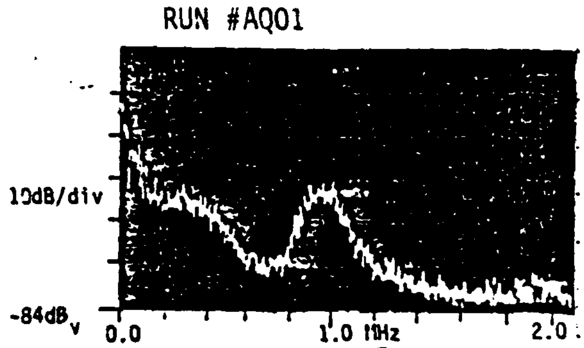


fig. 7

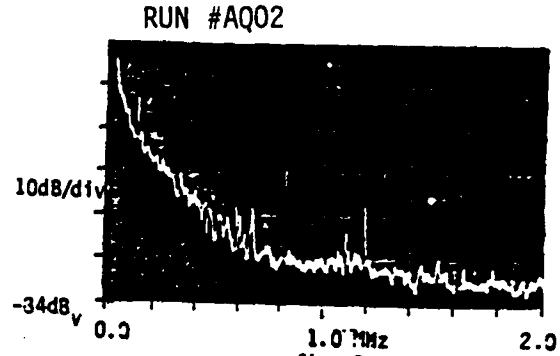


fig. 8

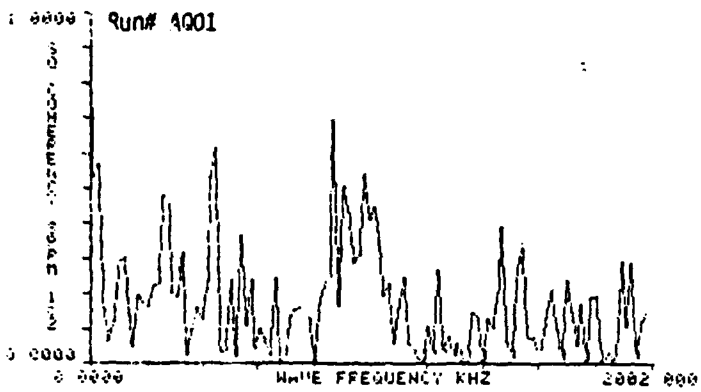


fig. 9

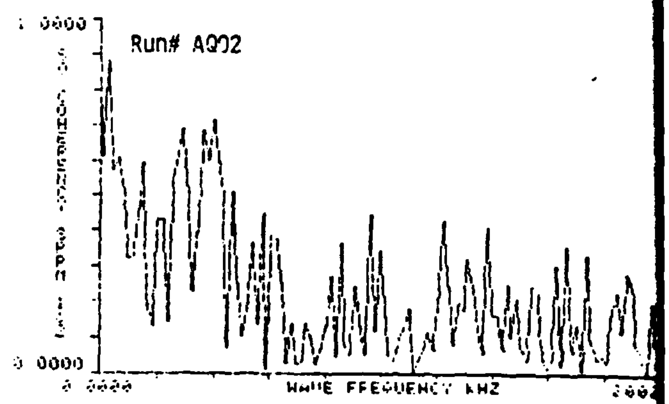


fig. 10

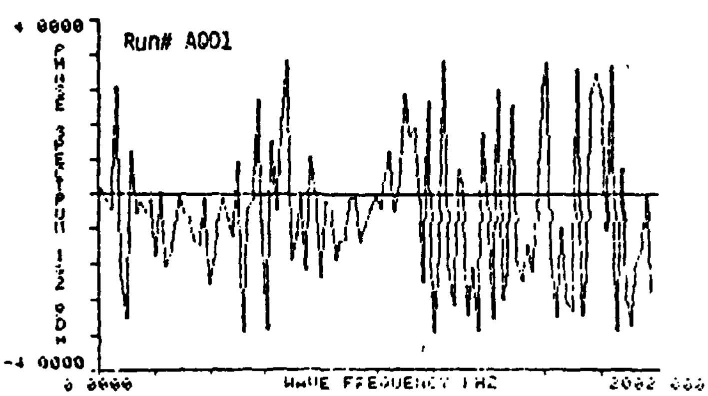


fig. 11

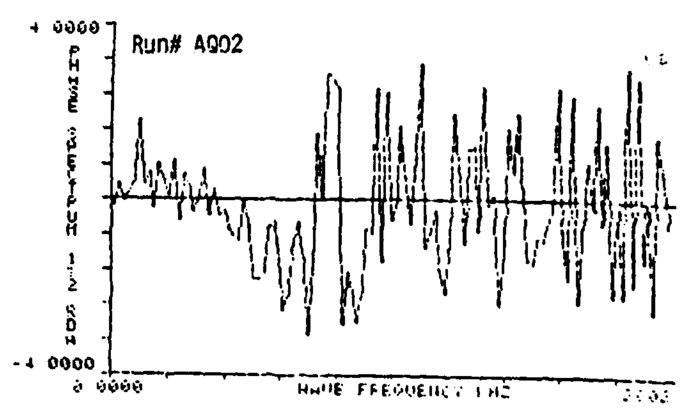


fig. 12

Although the high frequency mode is clearly damped in Figure 8, some enhancement at the low frequency is evident. The effect of damping is extremely critical in terms of the amplitude and frequency of the effector signal. Variation in frequency of a few percent will produce an enhanced spectrum. The signal amplitude had been carefully adjusted to yield optimum damping for Figure 8.

Figures 9 thru 12 show the squared coherency and phase spectrum for runs AQ01 and AQ02. The effect of damping is shown in the coherency with a reduction in the coherency at higher frequencies with damping.

The Effective Collision Frequency

Closure for Maxwell's Equations and the Lorentz force law in a plasma requires a relation which relates the densities of induced charges and currents to the electric field E, (or the relations of D to E). In linear electrodynamics these relations take the forms;

$$j_i(t,r) = \int_{-\infty}^{t} dt' \int dr' \varepsilon_{ij}(t,t',r,r')E_j)(t',r')$$

and

$$D_i(t,r) = \int_{-\infty}^{t} dt' \int dr' \sigma_{ij}(t,t',r,r')E_j)(t',r')$$

These equations relate the currents and charges induced in the medium at time t and space r to the field values at all previous times and

at any point. Hence frequency and wavelength dispersion are given by the functions σ_{ij} and ε_{ij}. The problem of determining these functions is fundamental to plasma physics.

The above integrals are taken with respect to the past ($-\infty$) in order to satisfy causality; and with the functions σ_{ij} and ε_{ij} taken as analytic, an extension to the above can be made relating the real and imaginary parts of θ_{ij} or ε_{ij}. These relations are known as the Kramers-Kronig formulas,[2] and will be used later.

The usual formula for plasma conductivity is written

$$\sigma = \frac{n e^2}{m_e v}$$

where v is the electron collision frequency for scattering centers (ions, neutrals, other electrons). A more rigorous definition of σ will account for momentum transfer between electrons and waves[3]. This can be introduced using an effective collision frequency and relating it to a frictional force F_{fr} in a momentum balance equation;

$$F_{fr} = - v_{eff}\, m_e n_o U_o.$$

This form of the collision frequency is used in the hydromagnetic equations to derive the Appleton equation[4], which relates the complex dielectric constant to basic plasma parameters. If electrons are exciting waves or undergoing oscillations the momentum loss by electrons can be expressed in terms of the momentum of waves emitted by electrons[3],

$$F_{fr} = \frac{2}{(2\pi)^3} \int \gamma W\left(\frac{k}{\omega}\right) dk$$

or

$$\nu_{eff} = \frac{2}{m_e n_o 4_o (2\pi)^3} \int \gamma W\left(\frac{k}{\omega}\right) dk$$

where γ is the electron's contribution to the instability growth rate and W is the spectral energy density of waves. Galeev and Sagdeev[3] extend the above for a non magnetized plasma to yield,

$$\nu_{eff} = \omega_{pe} \frac{W}{n_o T_e}$$

where W is now the energy density of waves with wavelengths on the order of the Debye radius. For drift wave turbulence, Horton[3] derives the total fluctuation energy density:

$$W = \sum_k W(k) = \frac{e^2 n_e}{2 T_e} \int dk \, [\phi(k)^2 + (\nabla_\perp \phi(k))^2]$$

with $\phi(k)$ the electrostatic contribution and $\nabla_\perp \phi(k)$ the density fluctuation contribution to the wave energy.

Measurements

The complex dielectric constant for electromagnetic wave propagation in the extraordinary mode (E_{rf} is perpendicular to static B_o) is given by the Appleton equation as:

$$\mu_{ex}^2 = 1 - \frac{\dfrac{\omega_p^2}{\omega^2}}{1 - j\dfrac{v}{\omega} - \dfrac{\omega_b^2/\omega^2}{1 - \omega_p^2/\omega^2 - j\,v/\omega}}$$

$$= [\mu - j\,X]^2$$

with the propagation constants related by

$$\alpha = \frac{\omega}{c} X \qquad \beta = \frac{\omega}{c}\mu\,.$$

The power of a microwave beam propagating through a plasma slab in the extraordinary mode attenuates as

$$\exp(-2\alpha d)$$

where d is the distance traversed through the plasma.

The above expression for μ_{ex} has a strong resonance in the vicinity of $\omega = \omega_b$, the gyro frequency. Numerical solutions for wave attenuation near $\omega = \omega_b$ for relavent plasma parameters yields the collision frequency as the full width at twice the minimum absorbed power at resonance. Figure 14 is a resonance curve taken using a Hewlett Packard 8510 Network Analyzer, on the uniform Penning discharge (Figure 13). The uniform Penning discharge is used for this measurement because of the problems involved if an axial gradient in the magnetic field exists. The

fig. 13
uniform Penning discharge

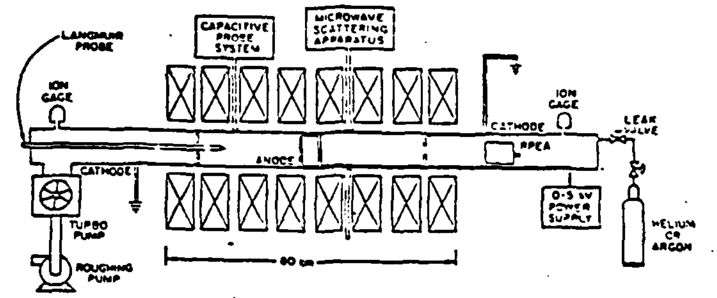


fig. 14
cyclotron resonance
absorbtion curve

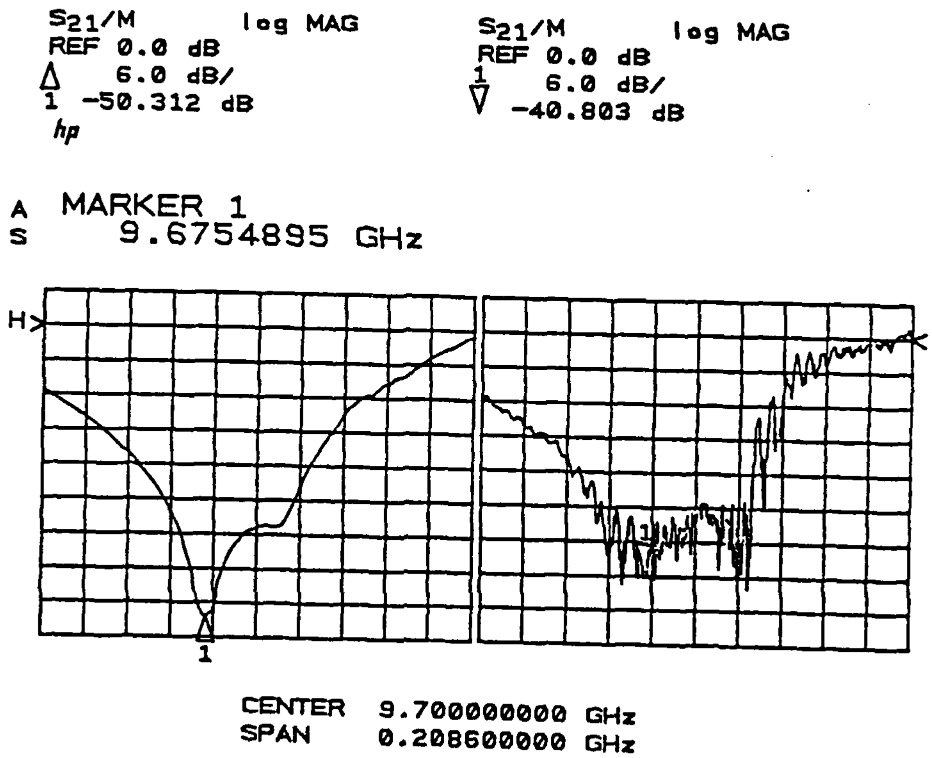
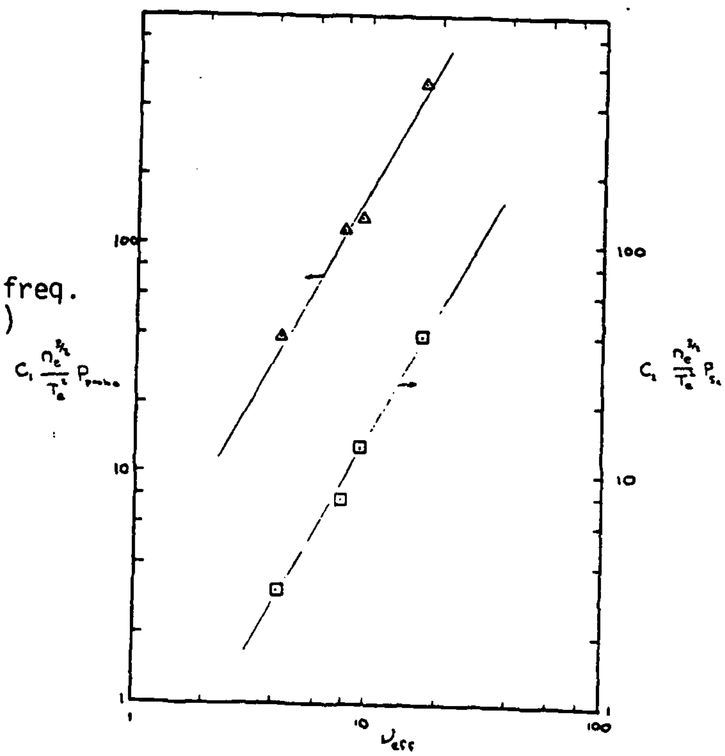


fig. 15

effective collision freq.
scaling (electrons)



need for signal averaging and smoothing are evident in the two curves in Figure 14 for accurate measurements of v_{eff}.

The turbulent spectra generated by drift wave turbulence is measured using capacitive probes and microwave scattering techniques. Capacitive probes are near field, infinitesimal monopole antennae. The current element of these antennae are very small compared to the field wavelengths and are located within 0.6λ of the source. Balanis[5] gives the real and imaginary components of radially moving power for a small dipole:

$$P = \frac{1}{2} \int\int_s E \times H^* \cdot \; ds = 7\left(\frac{\pi}{3}\right) \left| \frac{I_o \ell}{\lambda} \right|^2 \left[1 - j\frac{1}{(kr)^3} \right]$$

$$= P_{rad} + j\,2\omega(W_m - W_e)$$

with I_o = current on antenna filament

η = free space impedance (377 ohms)

P_{rad} = time averaged radiated power

$2\omega(W_m - W_e)$ = time averaged reactive power

For near field conditions the time averaged electric energy dominates and hence the power sampled by a "capacitive" probe will be proportional to the electric field energy in the turbulent waves;

$$W_e \,\alpha <E^2> = K^2 <\phi^2>$$

Microwave scattering is accomplished using a homodyne detection system[4] at $f_0 = 12$ GHz. The scattered microwave power is given approximately by

$$P_s \simeq \frac{P_i}{A} r_o^2 v^2 n_e^2 \Delta\Omega_r$$

where $\Delta\Omega_r$ = solid angle of receiver horn

r_o = classical electron radius

V = scattering volume

A = cross sectional area of incident microwave beam

n_e = fluctuating number density of electrons

P_i = incident microwave power

The ratio n_e/n_o for the plasma studied is typically a few percent. The Boltzman relation

$$\frac{n}{n_o} = \exp\left(\frac{e\phi}{T_e}\right)$$

is assumed valid on the edge of the plasma to yield

$$\frac{n_e}{n_o} \approx \frac{e\phi}{T_e}$$

or

$$n_e \simeq \frac{e\phi}{T_e} \; \frac{n_o e}{T_e} \phi$$

With the scattering beam oriented in the extraordinary mode so that only fluctuations in number density perpendicular to B_0 are observed, then

$$\nabla_{\perp} n_e = \frac{n_0 e}{T_e} \nabla_{\perp}\phi$$

or

$$n_e = \frac{n_0 e}{K T_e} \nabla_{\perp}\phi$$

Hence the scattered microwave power is directly related to the number density term in Horton's expression for drift wave energy.

The integrated power detected for both capacitive probe and microwave scattering is plotted vs. the measured collision frequency in Figure 15 (log-log plot). The slope for both curves is approx. 1.8. This discrepency with the theoretical value of unity is partially due to the integration of the detected power including frequencies with wavelengths much larger than the Debye length and, of course, to the presence of the magnetic field.

II. Current Literature

Drift Waves

Drift waves are electrostatic plasma waves resulting from instabilities due to density and/or temperature gradients as well as cross field (E x B) effects. The electric field for drift waves is oriented in the direction of propagation and satisfies the electrostatic equation

$$E = -\nabla\phi.$$

Drift waves generally have long axial wavelengths with perpendicular wavelength usually shorter than the driving temperature or density gradients. These gradient lengths are given by

$$\frac{1}{r_n} = -\frac{1}{n}\frac{dn}{dr} \qquad \frac{1}{r_T} = \frac{1}{T}\frac{dT}{dr}$$

The frequencies of drift waves are typically below the ion cyclotron frequency and are usually characterized by the diamagnetic frequency[3];

$$\omega_n = k_\perp \frac{cT}{\pm eBn}\frac{dn}{dr}$$

The principal motion of ions and electrons across magnetic field lines due to drift waves is given by the E x B guiding center drift velocity:

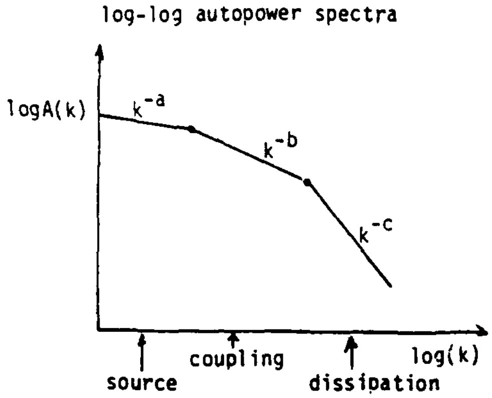
$$V_E = \frac{E \times B}{B^2}$$

This drift is due to the collective effects of the various drift waves and leads to anomalous transport (particles escaping confinement radially). The small component of the wave's electric field, parallel to the static magnetic field B_0, produces plasma oscillations (hence currents) which result in a small B that is perpendicular to B_0. This leads to a second loss mechanism (see Horton ref. 3).

The treatment of drift waves is usually done with kinetic theory[3], however some modes can be treated with a fluid (MHD) approach[6,3]. Typical instabilities leading to drift wave production are; universal instability (density gradient driven), inverse electron Landau damping, dissipative drift instability (finite resistivity effects), and various trapped particle instabilities. A treatment of the linear growth of these and other instabilities related to drift wave production are given by Mikhailovsky in ref. 3 and Miyamoto.

Finite resistivity treatments introduce collision frequency effects to drift wave instabilities. Linear instability growth rates are usually directly proportional to the appropriate collision frequency and can be either stabilizing or destabilizing, (see the treatment of dissipative trapped particle instability by Miyamoto).

The nonlinear evolution of drift waves leads to the formation of drift wave tubulence with broad frequency spectra (see Figures 2, 7, 8). These spectra can be viewed on log-log axes and are typically divided into three regions; source, coupling, and dissipation.



The source region is where energy is being injected into the spectrum, perhaps by a particular instability. The coupling range is typically where energy is being transferred from one frequency to another by some scattering or parametric process. Coupling processes can occur via, particle-particle, wave-particle, and wave-wave interactions as well as combinations of the these. These processes are covered in depth by Galeev and Sagdeev[3] for weakly turbulent plasma.

The dissipation region is characterized by some damping process by which wave energy is thermalized. Landau damping and/or viscous dissipation characterize this region for a plasma. The applicability of linear Landau damping is whether the Landau damping time $1/\omega_L$ is less than the period of oscillation of a particle in the potential well of the wave,

$$\frac{1}{\omega_i} < \tau_{osc}$$

where

$$\tau_{osc} = \left(\frac{m}{ekE}\right)^{1/2}$$

and the damping decrement δ due to Landau damping is given by[1],

$$\delta \simeq -\sqrt{\frac{\pi}{8}}\,\frac{\omega_{pe}}{K^3 r_{De}^3}\exp\left(-\frac{1}{2k^2 r^2 De}-\frac{3}{2}\right).$$

The degree to which Landau damping or viscous damping dominate will be determined by the smaller of the Landau damping time $1/\omega_L$ or the effective collision frequency v_{eff}.

An experimental investigation on density-gradient driven strong turbulence by Pecsel: et al[7] was performed on a low-β plasma column with $T_e > T_i$. The experiment was designed to make Taylors hypothesis effective so that comparison between theoretical and experimentally measured spectra could be made. Taylor's hypothesis yields: $\omega = k\ V_o$ (see Figures 6) implying the turbulent flow field moves past a detecting probe at a high rate of speed. Power law spectra $\sim k^{-a}$ were observed.

Drift Vortices

The nonlinear evolution of drift waves can also lead to the formation of relatively coherent structures called drift vortices.[8] These vortices resemble Rossby waves in the atmosphere and are governed by the Hasegawa-Mima[9] equation for density gradient driven waves and the Petviashvili[10] equation for temperature gradient driven waves. The dynamics of these two-dimensional vortices are of interest because of their long lifetimes and implications for radial transport. The Petviashvili equation is of the KdV type admitting soliton solutions.

Parametric Process

Parametric excitation is the nonlinear instability of two waves (an idler and a signal) by a modulating wave (pump wave) due to some mode-coupling interaction. The pump wave is usually of large amplitude and modulates a parameter of the system or media. The modulated parameter typically has a threshold above which its value becomes dependent on the pump wave amplitude (such as a capacitor with a charge dependent capacitance). For second order self oscillating systems this phenomenon takes the form of the Mathieu equation

$$x + \omega_o^2[1 - 2\varepsilon \cos \omega t]x = o$$

The extension to dissipative waves in a plasma is done by Mima and Nishikawa[3], as well as Nishikawa and Liu[11], and Galeev and Sagdeev[3]. The solution of some types of Mathieu equations is given by Mathieu functions but in general requires perturbation techniques.[20]

The most common and simplest example for parametric excitation is the three-wave interaction satisfying the matching conditions,

$$\omega_o = \omega_i + \omega_s$$

$$k_o = k_i + k_s$$

These conditions were exploited by Decker and Levine[13] to couple a large amplitude plasma instability to a damped-mode wave with the application of a suitable pump wave. Using the equations for weak parametric coupling circuits the plasma process was modeled theoretically. Hasegawa et. al.[14] presented a theoretical discussion of the parametric

excitation and quenching of longitudinal waves observed by Obiki et. al.[15]. These results all dealt with essentially periodic oscillations as opposed to quasi periodic.

A general set of relations for nondissipative parametric systems with periodic oscillations are the Manley-Rowe relations[16,17,3]. These relations are for the power flow between a set of oscillators coupled through a nonlinear network. When the parametric conditions above are satisfied for three wave interaciton and the low frequency wave is generated by the excitation of a high frequency wave, the Manely-Row relations imply that the ratio of energy flow is the same as the ratio of frequencies.

An extension for coherency measurements was made by Kim et. al.[29] for quadratically nonlinear systems. The application to plasma density fluctuations and potential fluctuaitons was reported.

Nonlinear Oscillators

The nonlinear phenomena of turbulence damping (Figures 8 and 9) under the influence of an external oscillator suggests an analogy to nonlinear self-oscillating dissipative systems under the influence of external harmonic action. Two such systems are considered below, one with a cubic nonlinearity and the other with a quadratic nonlinearity. Although both systems are only single degree of freedom systems, perturbation techniques are required to solve the governing ordinary differential equations.

The first example is taken from Nayfeh and Mook.[19] Consider the equation

$$\ddot{u} + \omega_0^2 u = \varepsilon\left(u - \frac{1}{3}u^3\right) + F(t)$$

where ω_0 is the self oscillating frequency, ε is a small parametric and F(t) is the forcing function. For non resonant excitation and excitation in a "hard" mode F(t) takes the form,

$$F(t) = A \cos \omega t$$

with A not small and ω far from ω_0 and from 1/3 ω_0. Using the method of multiple scales[20] a solution of the form

$$u(t;\varepsilon) = = U_0(T_0, T_1) + \varepsilon U_1(T_0, T_1)$$

is sought. To order ε, the solution is

$$u(t) = a(t)\cos(\omega_0 t + b) + \frac{A}{\omega_0^2 - \omega^2}\cos \omega t + 0(\varepsilon)$$

with

$$a^2 = \frac{4\eta}{\omega_0^2 + \left(\frac{4\eta}{a_0^2} - \omega_0^2\right)\exp\left(-\eta T_1\right)}$$

and a_0 is the initial amplitude and η is given by

$$\eta = 1 - \frac{\omega^2 A^2}{2(\omega_0^2 - \omega^2)^2}$$

Consequently, the application of a large forcing function results in the interaciton of particular and homogeneous solutions via the cubic (positive) damping term to alter the linear (negative) damping term and result in net damping of the self oscillation amplitude a.

The second example is taken from Migulin[18] and deals with a quadratic nonlinearity. A Thomson oscillating system is modeled as

$$x + (1 - \xi)x = (k + bx + \gamma x^2)x + A \sin pt$$

with

$$\xi = 1 - \frac{\omega_o^2}{\omega^2} \qquad \text{and} \qquad p \simeq n\omega_o$$

Using the method of slowly varying amplitude a solution of the form

$$x = Q \sin pt + u \cos \omega_o t + v \sin \omega_o t$$

where u and v are slowly varying functions of time and

$$Q = \frac{P}{1 - n^2} .$$

A solution for the magnitude of the self oscillation is given for $n = 2$ as

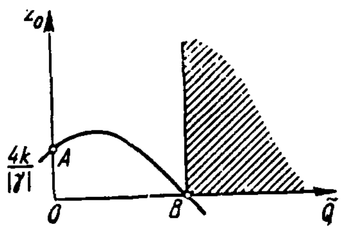
$$z_o = 0 - \frac{4}{\gamma} \left| K + \frac{1}{2} \gamma Q^2 \pm \sqrt{4b^2Q^2 - \xi^2} \right|$$

with z_o the non-zero steady-state amplitude of

$$z^2 = u^2 + v^2 .$$

This amplitude is plotted for n = 2 below for the nonautonomous mode (k > o, r < o) as a function of the driving amplitude. The shaded region corresponds to force oscillations with frequency p.

These examples, although for relatively simple systems, exhibit characteristics similar to the damping phenomena observed in Fig. 8 to Fig. 9. Careful tuning of both frequency and amplitude were required for the plasma mode damping. Near resonance conditions $\omega \approx \omega_0$ all three systems exhibit "pulling" or "entrainment". The self-oscillating frequency be comes the same as the driving frequency. For the plasma pulling by as much as .5 ω_0 has been observed, $(\omega - \omega_0) = \pm .5\ \omega_0$. This technique is sometimes used to determine instability growth rates.



The amplitude of self-oscillations under an external force with a double frequency.

(from ref. 18)

Routes to Turbulence

The transition to turbulence is currently a field of intense study both experimentally and theoretically. Some interesting references related to both classical fluids and plasma physics are Eckmann and Ruelle[21], Hunt[22], Swinney and Gollub[23], Horton and Reichl.[24] Actual routes to turbulence centers on the study of dynamical systems usually in the form of differential equation systems or evolution type equations. Techniques from bifurcation theory[25] are usually applied to describe how a system evolves from steady state stable solutions, to quasi periodic and then chaotic solutions as some control parameter is varied. Although these studies can become highly mathematical, the subject has been reviewed in anticipation of an appropriate scenario for drift wave turbulence. If such a scenario were found applicable then the process of turbulent enhancement and damping could be studied in terms of the altering of successive bifurcations through a parametric or forcing function excitation.

The Ruelle-Taakens-Newhouse scenario[26] is reviewed below because of recent results by Biskamp and Kaifen[27] for three wave interaction of drift waves and the results of flow past a cylinder by Sreenivasan.[29]

Evolution equations of the form:

$$\frac{d}{dt} x(t) = F(x(t))$$

behave in the following manner for dissipative systems

$$\sum_{i=1}^{m} \frac{\partial F(x)}{\partial x_i} < 0$$

where m is the number of degrees of freedom of the system. For F controlled by some parameter μ write $F = F_\mu$.

The Ruelle-Takens-Newhouse scenario assumes a steady state solution to $x = F_\mu(x)$ exists for some $\mu < \mu_c$ where μ_c is a critical value, and that this solution loses its stability through a Hopf bifurcation[29]. That is a pair of complex eigenvalues of

$$A_{ij} = \left.\frac{\partial F(x)}{\partial x_i}\right|_{x=x_\mu}$$

crosses the imaginary axis, or exp A_{ij} has eigenvalues crossing the unit circle (see Fig. 19). This implies that the steady-state solution has become oscillatory. It is further assumed that this process occurs three times in succession and each solution is essentially independent of the previous one. If these occur then a strange attractor may exist. The strange attractor has a domain of attraction associated with it best visualized by Figure 19 in comparison to Figure A1 of Figure 18.

The sequence of power spectra in Figure 20 illustrate the above scenario for Rayleigh-Benard heat transport for differential heating[23]. Similar results have been obtained for the formation of Taylor vortices for flow between rotating concentric cylinders[23]. In both cases the appearance of a third harmonic is accompanied by broadband aperiodic signals. The presence of finite noise levels does not effect the outcome of a RTN scenario.

Biskamp and Kaifen[27] apply a three wave interaction to reduce the following set of drift wave equations

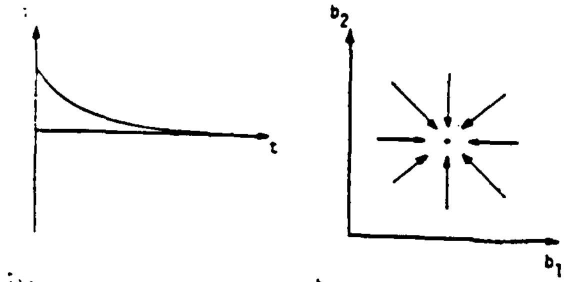


FIGURE A1: Stable node. (point attractor)

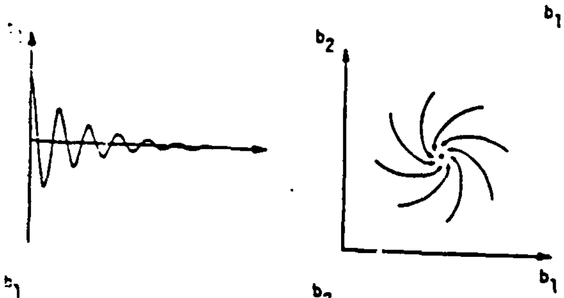


FIGURE A2: Stable focus. (point attractor)

fig. 18

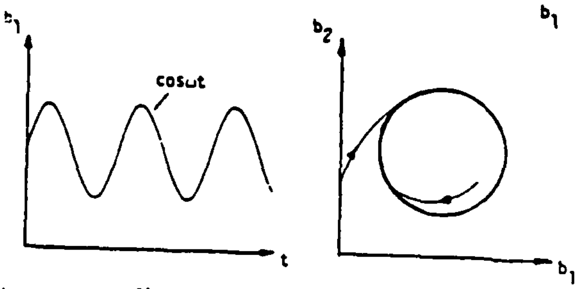


FIGURE A3: Limit cycle.

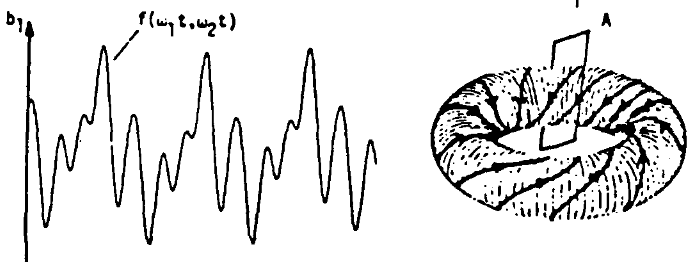


FIGURE A4: Two-torus. (perspective view)

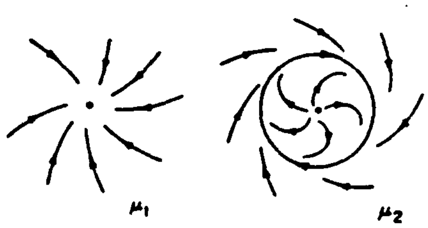
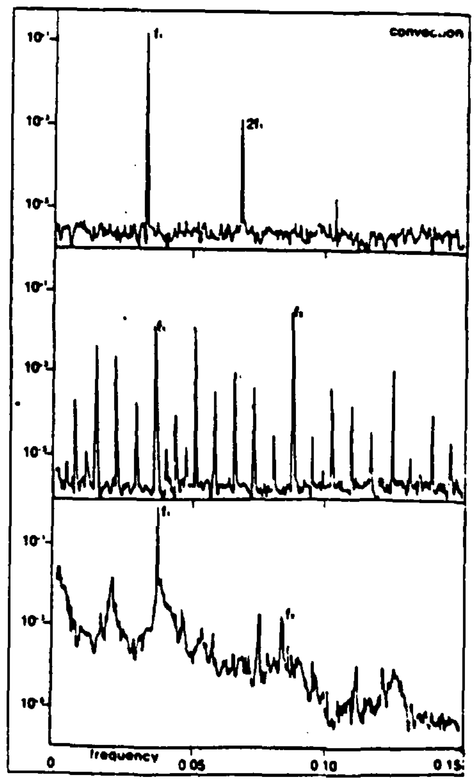


FIG. 4. Phase portraits illustrating Hopf bifurcation.

fig. 19 (ref. 21)

fig. 20
(ref.21)



H-40

Power spectrum of heat transport at different heating in Rayleigh-Bénard convection.

$$\frac{\partial n'}{\partial t} + \nabla_n J + \nabla_\perp \cdot \; [n(v_e + v_p)] = 0$$

$$\frac{\partial J}{\partial t} + \frac{1}{m} \nabla_\parallel P + \frac{ne}{m} \nabla_n \phi + v_e \cdot \; \nabla_\perp J = 0$$

where J is the parallel ion flow due to drift wave and v_e and v_p are the polarization drifts given by

$$v_e = - c \frac{\nabla_\perp \phi \times B}{B_o^2}$$

$$v_p = - \frac{c}{\omega_{pi} B_o} \left(\frac{\partial}{\partial t} \partial_\perp \phi + (v_e \cdot \; \nabla_\perp) \partial_\perp \phi \right)$$

Numerical solutions for the reduced system derived by

$$\phi_j(t) = a_j(t) \exp[- i\alpha_j t]$$

showed the behavior of $a_j(t)$ to follow a RTN scenario.

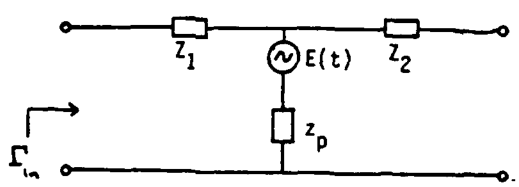
III. Future Research

Experimental

The modified Penning discharge is currently being changed to a uniform Penning discharge. The uniform magnetic field will facilitate effective collision frequency measurements and produce a more "two dimensional" discharge in which controlled perturbations (via effector probe) are introduced.

A two channel microwave scattering system (f_0 = 16 GHz) is currently being designed. Using two channel microwave scattering the density fulctuations associated with drift wave phenomena can be detected, hence the perpendicular and parallel current densities could be inferred.

The measurement of the ion effective collision frequency will be attempted in the next few months. Since the ion gyro frequency is typically below a few megahertz, techniques other than those used for measuring the electron collision frequency must be used. Antenna resonances or cavity resonances can be employed but are complicated in that the measurement is on an active system. Consider the following circuit,



circuit model for resonance measurement

The source E(t) enters because of the electrostatic fluctuations due to turbulence. In order to measure the resonance properties of the plasma, z_p must be de-embedded from the system resonances Z_1, Z_2 and the signal properties of E(t). The presence of E(t) requires signal rejection capabilities for network analyzer measurements. This is why such measurements have been postponed until the modification of the lab's network anayzer.[30]

An alternative to the above technique is to launch ion-acoustic waves along magnetic field lines and measure the wave's dispersion properties. The dispersion equation for such waves can be derived with fluid equations as[31],

$$1 - \frac{\omega_{pe}^2}{\omega(\omega - i\,v_e) - k^2 U_e^2} - \frac{\omega_{pi}^2}{\omega(\omega - i\,v_i) - k^2 U_i^2}$$

For the conditions $\omega, v_c < \omega_{pi}$, Hatta and Sato[32,31] launched an ion-acoustic wave in a non magnetized plasma and measured the phase difference vs frequency and amplitude attenuation vs. distance (Figure 22, 23). The term v_c is given by

$$v_c = \frac{m_e v_e + m_i v_i}{m_e + m_i} \approx v_i$$

The dispersion relation above yields the following in the limit studied by Hatta and Sato;

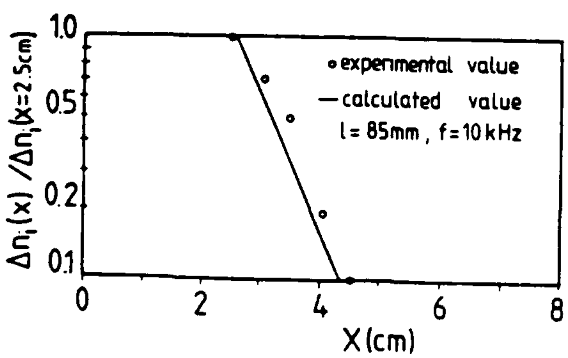
$$\Delta\theta = \frac{\sqrt{\nabla_c\,\omega}}{c_s}\, d$$

$$k_i = \frac{k_o^2}{2}\left[\left(1 + \frac{v_c^2}{\omega^2}\right)^{1/2} - 1\right]$$

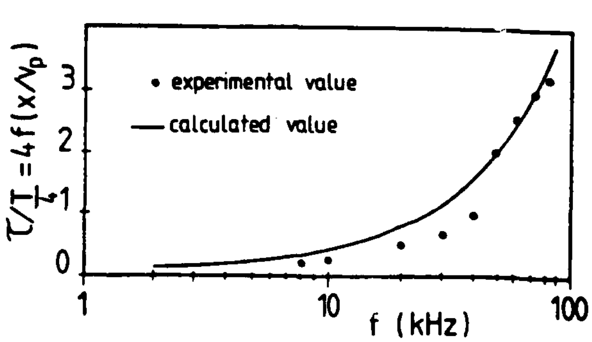
with k_i the imaginary wave number used for computing the damping and C_s the ion sound speed given by

$$C_s = \left(\frac{T_e + 3T_i}{m_i}\right).$$

The extension of this work to measurements on a turbulent plasma would require new derivations of $\Delta\theta$ and k_i for the condition $v_c \geq \omega_{pi}$. For electron collision frequencies it has been observed that $v_e \geq \omega_{pi}$ for UTK plasma conditions. The launching and measuring of these wave properties could easily be accomplished using the effector probe and network anayzer.



Dependence of the attenuation of amplitude on the distance (x) from G. (After Hatta and Sato, 1962.)



Phase difference versus frequency (f). (After Hatta and Sato, 1962

Theoretical, Numerical

The derivation of the Hasegawa-Mima and Petviashvili equations[8] considers slab geometry with an external magnetic field B in the z direction and density and temperature gradients in the x direction. The ion density continuity equation becomes

$$\frac{\partial n_i}{\partial t} + \nabla \cdot (n_i u_i) = 0$$

The two dimensional ion velocity is assumed to obey the reduced momentum equation

$$\frac{du_i}{dt} = \frac{e}{m_i}(E + u_i \times B)$$

with the electric field taken as electrostatic, i.e.

$$E = -\nabla\phi \ .$$

The potential ϕ is taken to follow a Boltzmann relation and is related to the ion and electron number densities by

$$\begin{aligned} n_i \approx n_e &\approx n_o(x) \exp \frac{e\phi}{T_e} \\ &\approx n_o(x)\left(1 + \frac{e\phi}{T_e}\right) \end{aligned}$$

Evoking the drift approximation (see Miyamoto ref. 6), the following form for u_i approximately solves the above momentum equation, for time scales large compared to the ion gyro period.

$$u_i = \frac{\nabla\phi \times B}{B^2} - \frac{1}{B\omega_{pi}} \frac{\partial n\phi}{\partial t} + [(\nabla\phi \times z)\cdot \nabla] \frac{\nabla\phi}{B\omega_{pi}}$$

Using the continuity equation with this expression and renormalizing yields

$$\frac{\partial}{\partial t}(\phi - \nabla^2\phi) + (\sim\phi \times z)\cdot (u_d^* + U_{dT} + \nabla \nabla^2\phi) = 0$$

where

$$U_d^* = -\nabla \ln n_o - \nabla \ln T_e$$

and

$$U_{dT} = - \nabla \ln T_e \ .$$

The Hasegawa - Mima term is given by

$$(\nabla\phi \times z)\cdot \nabla \nabla^2\phi,$$

with the Petviashvili term given by

$$(\nabla\phi \times z)\cdot v_{dT} \phi \ .$$

Analytic solutions to the renormalized equation in ϕ are known to exist for the individual cases of strong temperature gradients and strong density gradients.

Assuming manageable boundary conditions can be imposed, a numerical solution of these equations could be attempted on an existing finite element code (Baker et al[33]). These solutions could be compared to known solutions for limiting cases and perturbation solutions for others.

IV. The Dissertation: A Discussion

The approach discribed above has a number of interesting aspects as well as subtle implications. A two variable, two dimensional system allows computations on an existing code (with modifications)*. The experimental apparatus allows the addition of energy to different regions of the turbulent spectrum. It is suggested that energy input at small scale sizes may produce enhancement of the effective collision frequencies. Direct measurements of these quantities would allow verification of this.

The damping of many physical systems are actually characterized by exponential damping. For a fluid dynamical system this may take the form

$$F_{fr} \propto \exp[\gamma_j^* \cdot <U>]$$

where $\gamma(u)$ is a damping function inherent to the nature of the flow and $<U>$ is a bulk averaging process. Expanding the exponential in a Taylor series;

$$F_{fr} \propto 1 + \gamma_1 <U_1> + \gamma_2 <U_2>^2 + \gamma_3 <U_3>^3 + \ldots .$$

Heuristically, the means by which linear, quadratic, cubic etcetera nonlinearities enter as dissipative phenomena is evident. The function of γ_1 may be such as to promote instability growth in a linear mode (resistive instabilities[3]) wereas the cubic and quadratic terms allow regeneration and dissipation in the context by which linear modes (homogeneous solutions) can interact with nonlinear modes (particular solutions) to

produce growth and saturation phenomena. As the γ's may be complex they would still have to satisfy casuality, and hence be related through Kramers-Kronig type relations. The interaction of modes have usually been in the context of the convection terms $(u \cdot \nabla)u$ and E x B. However the context in which these modes interact thru dissipative phenomena may be equally as fundamental to the transition to turbulence.

In classical fluid dynamics the concept of eddy viscosity and negative viscosity phenomena are analogous to the above concepts of coefficients of regeneration and dissipation. (Eddy viscosity phenomena often result in viscsities orders of magnitude larger than free stream viscosity). The competition between cubic and quadratic nonlinearities may be manifested in pipe flow[23] where the flow alternately becomes unstable and stable for increasing Reynolds number.

The discussion above would suggest that the common technique of Reynolds decomposition

$$U = U_0 + u$$

with $u << U_0$ (u is the fluctuating component) is not acceptable for nonlinear dissipative phonema. The flow field U is intimately related to the dynamics of the γ's with the γ's integral functions of U.

*Drift waves are convective instabilities i.e. growth occurs in time accompanied by spatial propagation as opposed to absolute instabilities which grow for all space in time. This implies the need for time accurate solutions.

V. Symbols

B	magnetic induction vector
c	velocity of light
D	electric displacement vector
E	electric field vector
e	electron charge
ε_{ij}	permitivity tensor
ε	small parameter
k	wave vector or number
$k_{\perp}$	wave vector perpendicular to state B field
$k_{\perp}$	wave vector parallel to state B field
λ	wave length
μ	real dielectric constant
n_i	number density of species i
m_i	mass of species i
θ_{ij}	conductivity tensor
ϕ	potential function
U	velocity
W	spectral energy distribution function
v, v_{eff}	collision frequency
ω	wave or applied signals frequency
ω_o	self excited frequency
ω_{bi}	cyclotron frequency species i
$\omega_{\rho i}$	plasma frequency species i
z, Z	complex impedence

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APPENDIX I

Title Pages, Tables of Contents, and Summaries of Proposals/Status Reports Submitted to ONR in Connection with Contracts N00014-80-C-0063 and N00014-K-0174

Unsolicited Proposal

"INVESTIGATION OF RF EMISSIONS FROM
ELECTRIC FIELD DOMINATED PLASMAS"

Submitted to

OFFICE OF NAVAL RESEARCH

by

Prof. J. Reece Roth
Ferris Hall
Department of Electrical Engineering
University of Tennessee
Knoxville, Tennessee 37916

for

Physical Sciences Div.
Office of Naval Research
800 N. Quincy St.
Arlington, VA 22217

PROPOSED DURATION: Three years

AMOUNT REQUESTED: $34.8k for 1st year

REQUESTED STARTING DATE: Oct. 1, 1979

PRINCIPAL INVESTIGATOR: J. Reece Roth
Phone: (615) 974-4446

BUSINESS CONTACT: Miss. Ann Rochelle
Phone: (615) 974-4438

J M Googe

Dr. J. M. Googe
Department Head

J. Reece Roth

Dr. J. R. Roth
Principal Investigator

L Evans Roth

L. Evans Roth
Vice Chancellor for Graduate
Studies and Research

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Unsolicited Proposal

"INVESTIGATION OF RF EMISSIONS FROM ELECTRIC FIELD DOMINATED PLASMAS"

1. EXECUTIVE SUMMARY

The present proposal describes a research program designed to investigate RF emissions from electric field dominated plasmas, in which a variety of turbulent, nonlinear phenomena occur. Much of the research effort covered by this proposal would be focussed on the newly-discovered RF emission at the geometric mean plasma frequency. This emission has been observed experimentally and described theoretically, but much work needs to be done to compare theory and experiment, to improve the efficiency of the RF emission process, and to develop mechanisms to extract sufficient RF power to be of interest for potential practical applications.

A potential application of the geometric mean plasma emission of particular significance to the Navy is the excitation of RF radiation by this mechanism in the lower ionosphere, at low frequencies which are capable of interfering with submarine communications. This emission mechanism is excited at frequencies given by

$$\nu_{gm} = \frac{737 n_e^{1/2}}{A^{1/4}} \text{ Hz}$$

where n_e is in electrons/cm^3, and A is the atomic weight of the background ions. A characteristic maximum number density in the ionosphere is about $n_e = 1.5 \times 10^7/\text{cm}^3$ at an altitude of 370 km, where atomic oxygen ions are dominant. The geometric mean emission frequency corresponding to these conditions is 1.4 MHz. If mirroring or

counterstreaming electrons were to penetrate below this altitude, all frequencies below this value could be excited, and the resulting RF radiation trapped in the cavity between the ionosphere and the earth.

The geometric mean plasma emission is probably the most interesting phenomenon known to occur in electric field dominated plasmas, insofar as possible naval applications are concerned. However, it is also intended during the course of the research covered by proposal to conduct exploratory investigations of a basic nature designed to detect and identify other RF emission phenomena which may occur in electric field dominated plasma.

The original experimental work which led to the discovery of the geometric mean plasma emission was part of a broader research program conducted at the NASA Lewis Research Center by Dr. J. Reece Roth, who will be Principal Investigator of the proposed research at the University of Tennessee. As the result of major program cancellations within NASA, all the equipment used in this earlier research is now surplus to NASA. There is good reason to believe that this equipment will be available to the University of Tennessee to conduct the proposed research if ONR support is forthcoming.

As part of the NASA research program on electric field dominated plasmas, it was found that in crossed-field configurations, such as the modified Penning discharge, strong radial electric fields, up to several kilovolts per centimeter, would penetrate both radially and axially. In these plasmas, the Debye lengths were much shorter than the radial distances over which the electric fields were observed to penetrate. These electric field dominated plasmas can be operated in a

steady state; can have work done on them by the electric fields produced by external power supplies; are subject to a wide variety of instabilities and turbulence; and have been observed to emit RF radiation at several frequencies, not all of which are well understood either theoretically or experimentally. Indeed, the geometric mean plasma oscillation may be only the first of several new emission mechanisms to be identified in electric field dominated plasmas.

The proposed budget covers a one year period starting as soon after October 1, 1979 as possible. It is anticipated that the research program will extend over a three year period, and that more funds will be needed in subsequent years than are requested for FY 1980, in order to hire additional staff, to operate the superconducting pilot rig facility, and to supplement the NASA equipment. The Principal Investigator, Dr. J. Reece Roth, will be available for two months during the Summer and for 10% of his time for the rest of the year. It is hoped that the University of Tennessee will be able to attract support from the AFOSR for research in this general area, in an amount approximately equal to the amount of this proposal. Should such support materialize, the more basic work related to properties of electric field dominated plasmas, and turbulent and nonlinear phenomena in them, would be done under Navy auspices, with work on aspects of the geometric mean plasma emission related to high power, pulsed RF emission being done for the AFOSR.

Renewal Proposal (Revised)
ONR Contract N0014-80-C-0063

"INVESTIGATION OF RF EMISSIONS FROM
ELECTRIC FIELD DOMINATED PLASMAS"

Submitted to

OFFICE OF NAVAL RESEARCH

by

Prof. J. Reece Roth
Ferris Hall
Department of Electrical Engineering
University of Tennessee
Knoxville, Tennessee 37916

for

Dr. Charles W. Roberson
Code 421
Physical Sciences Div.
Office of Naval Research
800 N. Quincy St.
Arlington, VA 22217

PROPOSED DURATION: 21 Months

AMOUNTS REQUESTED: $35,000 for Jan. 1, 1981-Sept. 30, 1981
$54,865 for F.Y. 1982

REQUESTED STARTING DATE: Jan. 1, 1981

PRINCIPAL INVESTIGATOR: J. Reece Roth
Phone: (615) 974-4446

BUSINESS CONTACT: Miss Ann Rochelle
Phone: (615) 974-4438

Dr. J. M. Googe
Department Head

Dr. J. R. Roth
Principal Investigator

CARL O. THOMAS
Dean for Research

12/10/80

ONR RENEWAL PROPOSAL

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RENEWAL PROPOSAL

for

ONR Contract N0014-80-C-0063

INVESTIGATION OF RF EMISSIONS FROM ELECTRIC FIELD DOMINATED PLASMAS

SUMMARY

This proposal requests the renewal of a one year contract with the same title, which has been supported by ONR at a level of $34.8K, and which is scheduled to terminate on December 31, 1980. This contract has accomplished, or will accomplish by the end of 1980, all of the first year goals in the original proposal, and in addition has made further progress not originally contemplated.

Under this contract, approximately $400,000 worth of surplus NASA RF and plasma-related diagnostic equipment has been shipped from the NASA Lewis Research Center to the University of Tennessee at Knoxville (UTK). This equipment has been unpacked, set up, and documented. Appropriate apparatus and diagnostics required to implement the proposed research for ONR have been set up and checked out, an able research assistant has been hired and has been with the contract since its inception on January 1, 1980, and we achieved the first plasma in the UTK Plasma Laboratory on July 11, 1980.

The electric field dominated plasma from which we expected to observe the geometric mean plasma emission is created by a modified Penning discharge in a magnetic mirror configuration with a five to one mirror ratio. This relatively high mirror ratio was chosen to better simulate the high

mirror ratios characteristic of the earth's magnetosphere. During the summer, we made qualitative observations of the electromagnetic emissions from this plasma, and observed a rich spectrum of emission peaks at various frequencies, in addition to a broad background of RF emissions over all frequencies from a few megahertz to more than a Gigahertz. The most prominent of these emission peaks is of the right frequency, and has the right functional dependence on plasma parameters, to be the geometric mean emission, the investigation of which was the main line of effort in the original proposal. The existence of RF emission peaks in addition to the geometric mean emission, and of broadband RF emission, were not anticipated, and deserve to be studied in detail. If such broadband emission were to occur in the earth's magnetosphere, interference with low frequency navigation beacons and submarine communications could result. By the end of calendar year 1980, it is anticpated that quantitative measurements will be available to definitively confirm the existence of the geometric mean emission frequency in this electric field dominated plasma, and to confirm the 1/4 power dependence of the emission frequency on the atomic mass number of the plasma ions.

Significant theoretical progress was made during 1980, which has resulted in four publications, including three conference abstracts and one journal length article which has been submitted for publication. This increased theoretical understanding is largely due to the efforts of Professor Igor Alexeff of the UTK faculty. The original theory of the geometric mean RF emission process has been extended to the case of finite ion kinetic temperatures. Finite ion temperatures do not affect the emission process in a fundamental way, and it has been shown that plasma

conductivities associated with the geometric mean emission process are far lower than any other known beam-plasma interaction process, including the anomalous conductivity of Buneman.

It is proposed to slightly expand the scope of the ONR contract. The level of support of $34.8K for calendar year 1980 would increase to $35K for the 9-month period Jan. 1, to Sept. 30, 1981, and to $54.9K for F.Y. 1982. This increased funding would allow us to hire a second research assistant, the responsibilities of whom would be to conduct exploratory investigations of the broadband emission and additional frequency peaks which have been observed from this electric field dominated plasma, and to document, in a quantitative manner, the functional dependence of these emission frequencies on the plasma characteristics. The proposed equipment budget would allow essentially the entire equipment budget for the 9-month period to be spent on a turbo-molecular pump which is needed to reduce to acceptable levels the base pressure of the vacuum system, and also to reduce the background contaminants that would otherwise be present during normal operation of the plasma. During F.Y. 1982, the equipment budget would be spent for two analog-to-digital convertors, which would be used in fluctuation studies.

Progress Report and
Renewal Proposal
ONR Contract N00014-80-C-0063

"INVESTIGATION OF RF EMISSIONS FROM ELECTRIC FIELD DOMINATED PLASMAS"

Submitted to

OFFICE OF NAVAL RESEARCH

by

Prof. J. Reece Roth
University of Tennessee
Knoxville, Tennessee 37996-2100

for

Dr. Charles W. Roberson
Code 421
Physical Sciences Div.
Office of Naval Research
800 N. Quincy St.
Arlington, VA 22217

PROPOSED DURATION: 24 Months

AMOUNTS REQUESTED: $124,958 Total
$59,198 for F.Y. 1983
$65,760 for F.Y. 1984

REQUESTED STARTING DATE: Oct. 1, 1982

PRINCIPAL INVESTIGATOR: J. Reece Roth
Phone: (615) 974-4446 (office)
974-4235 (Lab)

BUSINESS CONTACT: Mrs. Chris Cox
Phone: (615) 974-8159

Lee Riedinger

Dr. Lee Riedinger
Acting Department Head

J. Reece Roth 4/27/82

Dr. J. R. Roth
Principal Investigator

Marla Peterson

Dr. Marla Peterson
Dean for Research

ONR CONTRACT N00014-80-C-0063

"INVESTIGATION OF RF EMISSIONS FROM ELECTRIC FIELD DOMINATED PLASMAS"

PROGRESS REPORT AND RENEWAL PROPOSAL

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PROGRESS REPORT AND RENEWAL PROPOSAL

for

ONR Contract

N00014-80-C-0063

INVESTIGATION OF RF EMISSIONS FROM ELECTRIC FIELD DOMINATED PLASMAS

I. SUMMARY

This proposal requests the renewal of an existing contract with the same title, which has been most recently supported by ONR at a level of $54,865 for FY 1982, and which is scheduled to terminate on September 30, 1982. This contract has accomplished, or will accomplish by the end of FY 1982, essentially all of the objectives which had been proposed. In addition, exploratory experimental investigations have revealed several interesting new phenomena, the physics of which is poorly understood at present, and which may represent a new discovery in the field of RF plasma emission.

The electric field dominated plasma from which we are observing RF emissions is a modified Penning discharge in a magnetic mirror configuration with a 5:1 mirror ratio. This relatively high mirror ratio was chosen to better simulate the high mirror ratios characteristic of the earth's magnetosphere. This plasma is unlike plasmas investigated in many other academic laboratories (and is like magnetospheric plasmas) in at least two respects; 1) the plasma is operated in the steady-state, thus providing an opportunity to take accurate experimental data even in the presence of high levels of noise and plasma turbulence; and 2) the modified Penning discharge plasma is penetrated by strong electric fields,

both radially and axially.

During the current contract, a firm infastructure has been built up for our continuing experimental investigations of RF plasma emissions. During the period of the current contract, we put into service a polarization diplexing microwave interferometer; a Langmuir probe system capable of operating in plasmas which float several kilovolts above ground; a 1/2 meter Fast-ie-Ebert visible spectrometer; and a retarding potential energy analyzer with which we routinely measure the energy distribution functions of ions leaking out the ends of the magnetic mirror. We also have continued the development and refinement of probes and antennae for measuring RF emissions over a wide range of frequencies up to 1 gigaHertz.

In addition to this progress in diagnostic development, we have also upgraded the magnet and vacuum systems. We installed on the vacuum system a Polycold Model PCT-200 cold trap chiller, which uses a special freon which allows us to cool the cold trap above the diffusion pump to temperatures below -130°C. This has reduced the impurity level and decreased the base pressure of the vacuum system, as it was intended to do, without the constant necessity of handling liquid nitrogen. We also have upgraded the magnetic field coil system. These improvements include the repair of a number of long-standing faults with the old DC coil power supply, and the modification of its control system to include a number of protective interlocks.

The experimental research program has produced a number of interesting results during the contract period. The steady-state modified Penning discharge has proven to be a copious emitter of RF radiation from below 1 megaHertz more than 1 gigaHertz. For example, we have observed

RF emission interfering with FM radio reception in the vicinity of 100 megaHertz at distances of several wavelengths from the apparatus. In the near field (that is, closer than 1 wavelength from the plasma) we have tentatively identified two physical processes which give rise to the observed emissions; emission at the electron plasma frequency; and emission at the geometric mean frequency. Emission at these frequencies is usually accompanied by high levels of background turbulence and the generation of multiple harmonics, with as many as 50 harmonics of the geometric mean emission frequency being observable in some instances. Another interesting observation, and still tentative at this writing, is the observation of a white noise spectrum from below one megaHertz up to beyond 1 gigaHertz, when the plasma is operated in argon gas with a trace of nitrogen impurity. This very broadband emission spectrum is observable in the far field in the FM radio band. These observations of nonlinear mode coupling in the RF spectrum, and broadband emission of harmonics and white noise, may relate to magnetospheric emission processes which could interfere with low frequency communications of interest to the Navy. In addition, a high power, pulsed version of such an RF emitter might be useful for jamming purposes.

Activities in the UTK Plasma Science Laboratory which are supported at least in part by the ONR contract have received favorable media coverage. These are discussed later in this report, and the newspaper articles etc., are included in Appendix A. A significant form of outside recognition related to the contract activities is that the Principal Investigator of this contract, Dr. J. Reece Roth, was elected an IEEE Fellow in January,

1981. The citation on his fellowship certificate reads "For developments in Superconducting Magnet Technology and Discoveries in Plasma Instabilities and Turbulence." Support provided by the Office of Naval Research under this contract has enabled him to continue the line of basic research on plasma instabilities and turbulence which was mentioned in this fellowship citation.

The research activities under this contract have resulted in a number of publications. A major discovery paper on the geometric mean emission frequency was written with partial support from this contract, and published in the Physics of Fluids in July, 1981. Reprints of this and other publications may be found in Appendix B of this report. There was one paper which will be presented at the International Conference on Plasma Physics in Goteborg, Sweden on June 10, 1982. A paper has been accepted for publication in the Proceedings of that conference, and will describe work supported by the current contract. In addition, there have been five presentations, either oral or poster, at major plasma meetings during the period of this contract. There was one paper at the May 1981 IEEE conference on plasma science at Santa Fe, New Mexico. There were two papers at the October APS Plasma Physics Division meeting in New York on October, 1981, and two papers supported by this contract are to be presented at the IEEE International Conference on Plasma Science at Ottawa, Canada in May, 1982. This contract has supported other activities on the UTK campus which have enabled us to make the UTK Plasma Science Laboratory and interesting and exciting place for our students, and these activities are described later in this report.

Significant progress in theoretical research was made during the period of this contract. The results of these theoretical investigations,

largely due to Professors Igor Alexeff and Douglas Birdwell of the Electrical Engineering Department, are summarized in the Physics of Fluids paper included in Appendix A. With the publication of that paper, theoretical work on these phenomena is well ahead of experimental confirmation, particularly in the area of anomalous conductivity. It is appropriate during the proposed contract period to focus attention on obtaining experimental data in the laboratory to check these theoretical conclusions, and to provide guidance for future theoretical research.

This proposal requests a level of support of $59,198 for FY 1983 and of $65,760 for FY 1984, for a total of $124,958 over the two year period starting Oct. 1982. The amount proposed for FY 1983 is a slight increase, of about $5,000, over the $54,865 which supported this contract in FY 1982. This would allow us to maintain the current level of effort, which involves 25% of the Principal Investigator's time, over FY 1983 and FY 1984, and continue the support of two half-time research assistants for that period. This budget includes sufficient funding for routine small parts and equipment, and the purchase of a turbomolecular vacuum pump mass spectrometer, and ion gage read-outs to further upgrade our vacuum system.

Report PSL 83-2

Status Report

Status Rpeort on Contract ONR N00014-80-C-0063 for the Period

June 1, 1982 to June 1, 1983

Submitted to

THE OFFICE OF NAVAL RESEARCH
PHYSICAL SCIENCES DIVISION

by

Prof. J. Reece Roth
Room 409 Ferris Hall
University of Tennessee
Knoxville, Tennessee 37996-2100

for

Dr. Charles W. Roberson
Code 421
Physical Sciences Division
Office of Naval Research
800 N. Quincy St.
Arlington, VA 22217

UTK Plasma Science Laboratory
Report No. 83-2

June 30, 1983

PRINCIPAL INVESTIGATOR: J. Reece Roth
Phone: (615) 974-4446 (Office) 974-6223 (Lab)

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Phone: (615) 974-8159

J. Reece Roth

Dr. J. R. Roth
Principal Investigator

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Status Report on Contract ONR N00014-80-C-0063 for the Period June 1, 1982 to June 1, 1983		5. TYPE OF REPORT & PERIOD COVERED Status Report
		6. PERFORMING ORG. REPORT NUMBER PSL 83-2
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9. PERFORMING ORGANIZATION NAME AND ADDRESS UTK Plasma Science Laboratory Room 101 Ferris Hall University of Tennessee, Knoxville		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS N.A.
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18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

PLASMA TURBULENCE, PLASMA PHYSICS, HIGH TEMPERATURE PLASMA, RF PLASMA EMISSIONS, ELECTRIC FIELDS, ELECTRIC FIELD DOMINATED PLASMAS, RF SOURCES, RF EMITTERS, PENNING DISCHARGE, REFLEX DISCHARGE, INTENSE MICROWAVE SOURCE, MAGNETOSPHERIC EMISSIONS.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This status report summarizes accomplishments supported by ONR contract N00014-80-C-0063 during the period from Junel, 1982 to June 1, 1983. During this year, exploratory investigations were conducted on an electric field dominated plasma generated in a steady-state modified Penning discharge operating in a water cooled magnet system with a 5:1 mirror ratio, and capable of a maximum magnetic field of 0.4 telsa. Additional diagnostic systems were placed into service during this contract period, including a high voltage Langmuir probing system for axial density, potential, and electron

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ABSTRACT

This status report summarizes accomplishments supported by ONR contract N00014-80-C-0063 during the period from June 1, 1982 to June 1, 1983. During this year exploratory investigations were conducted on an electric field dominated plasma generated in a steady-state modified Penning discharge operating in a water-cooled magnet system with a 5.7:1 mirror ratio, and capable of a maximum magnetic field of 0.4 tesla. Additional diagnostic systems were placed into service during this year. These include a high voltage Langmuir probing system for axial density, potential, and electron kinetic temperature profile measurements, and the developement of computer software to obtain best-fitting ion energy distribution functions to data from the retarding potential energy analyzer.

Phenomena observed during this year include RF emissions which have been observed at frequencies from 0.5 MHz to 2.0 GHz; and also ion energy distribution functions which ranged from thermalized, maxwellian distributions with kinetic temperatures on the order of kev, to monoenergetic energy distribution functions with kilovolt energies. Also observed were axial electrostatic potential, number density, and kinetic temperature profiles which revealed electric fields along the magnetic field lines of more than one hundred volts per centimeter, and the formation of local electrostatic potential wells. These local potential wells are capable of trapping ions at a location between the minimum and maximum magnetic field. Also observed were a rich variety of nonlinear mode coupling phenomena among the various RF emissions from the plasma.

This plasma is capable of operating for hours at a time under conditions that allow ready investigation of physical processes responsible for RF emissions and ion heating. This plasma resembles, and is potentially a test bed for, physical processes which may occur in reflex discharges and/or intense radiation and particle beam

sources which are pulsed on time scales too short to allow ready investigation of their physics.

Other activities supported by this contract include the preparation of a trip report to a "foreign" scientific meeting, the 1982 IEEE International Conference on Plasma Science, held in Ottawa Canada, May 17-19, 1982. A copy of this trip report is included as appendix D for the sake of completness. Supported during this year was attendence at the International Conference on Plasma Physics, Goteborg Sweden, June 9-15, 1982. A trip report is included as appendix C. During this year we also started the development of an analog to digital data handling system to make it possible to analyze in detail time series data from capacitive and Langmuir probes. This instrumentation and its associatd software will make it possible to analyze at least two simultaneous channels of density or potential fluctuation data and reveal a wide variety of information on their cross-power spectra, coherence, probability density functions, group and phase velocity, and other statistical properties of plasma turbulence in the electric field dominated plasmas under investigation. Finally, the very welcome award of a supplemental $30,000 for additional instrumentation will be spent principally on a LeCroy 3500 transient recorder system which will bring our laboratory data handling and reduction procedures up to state-of-the-art levels, although it will require some software development, since plasma related data reduction software is not available on a commercial basis.

RESEARCH PROGRAM

Objectives

This research program was initiated on January 1, 1980, and is supported by ONR contract N000-14-80-C-0063 under the technical oversight of Dr. Charles W. Roberson of the Physical Sciences Division of the Office of Naval Research. This contract was

THREE-YEAR RENEWAL PROPOSAL
AND STATUS REPORT FOR

N00014-80-C-0063

For the Period

Oct. 1, 1984 to Sept. 30, 1987

J. Reece Roth

Principal Investigator

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
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		6. PERFORMING ORG. REPORT NUMBER PSL 84-2 84-2
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report proposes the extension of ONR Contract N00014-80-C-0063 for a 3 year period from Oct. 1, 1984 to Sept. 30, 1987. The proposed level of effort will fund the Principal Investigator for one quarter time, and will support two half-time graduate assistants in their experimental research program in the UTK Plasma Science LAboratory. The proposed level of funding is $69,658 for federal fiscal year 1985; $74,896 for FY 1986; and $84,882 for FY 1987. The total funding over this proposed 3 year period would amount to $229,436.

Renewal Proposal

Three-Year Renewal Proposal for the Period
October 1, 1984 to September 30, 1987

and

Status Report for the Period
June 1, 1983 to June 1, 1984

for

ONR Contract NOOO14-80-C-0063

Submitted to

THE OFFICE OF NAVAL RESEARCH
PHYSICAL SCIENCES DIVISION

by

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Room 409 Ferris Hall
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Knoxville, Tennessee 37996-2100

for

Dr. Charles W Roberson
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UTK Plasma Science Laboratory
Report No. 84-2

Submission Date: June 22, 1984

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SUMMARY

This document contains a status report on ONR Contact NOOO14-80-C- 0063 for the period June 1, 1983 to June 1, 1984, and a proposal for a 3 years extension of this contract. This contract has supported experimental investigations of an electric field dominated plasma generated in a steady-state modified Penning discharge which operates in a water-cooled magnet system with a 5.7 to 1 mirror ratio, and which is capable of a maximum magnetic field of 0.4 telsa. This plasma is capable of operating for hours at a time under conditions that allow ready investigation of physical processes responsible for ion heating and RF emissions at microwave frequencies. This plasma resembles, and is potentially a test bed for, physical processes which may occur in reflex discharges and/or intense radiation and particle beam sources which are pulsed on time scales too short to allow ready investigation of their physics.

During the past year, additional diagnostic systems were placed into service. These include two specially designed antennas which allow very broadband detection of RF plasma emissions over a frequency range from 100 megaHertz to 1.2 gigaHertz, without significant interference by the antenna response pattern. These antennas are also calibrated to permit absolute measurements of the RF emitted from the plasma. Another key diagnostic improvement was development of software for our LeCroy 3500 transient recorder system, which allows the on-line reduction of data trom Langmuir probes and retarding potential energy analyzers. This software has made it possible to greatly speed up the data taking process while at the same time improving the precision of plasma parameter measurement.

Some of the phenomena observed during this year include axial and radial profiles of plasma parameters in the modified Penning discharge, while at the same time making RF emission measurements with our calibrated antennas. These

measurements not only confirmed previous observations of broadband RF emission from a few hundred megaHertz to many gigaHertz; but they also revealed strong radial and axial electric fields in the plasma with values on the order of hundreds of volts per centimeter in some cases. We also observed the production of energetic ions with characteristic energies of keV and energy distribution functions ranging from monoenergetic to Maxwellian; very high levels of plasma turbulence, and peaks in the plasma fluctuation and RF emission spectra corresponding to the geometric mean emission frequency.

Two broad-band antennas were developed, a conical spiral and planar log spiral antenna, both of which had a nearly flat frequency response in the range from a hundred megaHertz to 1.2 gigaHertz, and both of which are calibrated to allow absolute measurements of the RF power emitted from the plasma. These antennas were used to measure the RF power emitted by the plasma, as a function of the plasma parameters. *It was found that in the present mode of operation, the* modified Penning discharge is converting up to about 0.1% of the input DC power into electromagnetic radiation between 100 megaHertz and 1.2 gigaHertz. The radiated power appears to be proportional to the electron number density, suggesting that the electrons in the emitting volume of plasma are turbulent, and are radiating incoherently, since coherent radiation, would have an emitted power proportional to the square of the electron density.

During the period of this report, Mr. Saeid Shariati, completed his master of science in electrical engineering degree with a thesis entitled "Computer Aided Reduction of Plasma Data". Mr. Shariati wrote up the software programs developed for the LeCroy 3500 transient recorder system, which allow the reduction of Langmuir probe, retarding potential analyzer, and charge exchange neutral energy analyzer data.

Other activity supported by this contract during the year following June 1, 1983 include 3 trips over the summer of 1983 to screen surplus equipment at the Warner-Robbins Air Force Base near Macon, Georgia; the Redstone Arsenal at Huntsville, Alabama, and the Bluegrass Depot near Lexington, Kentucky. These trips were very productive, and resulted in our obtaining over 400 individual items of microwave and electronic test instrumentation, the total value of which, new, was close to 1 million dollars. This equipment was checked out and calibrated when it arrived at the UTK Plasma Science Laboratory, has been incorporated into our research program, and produced some of the results which were obtained during the past year.

Another major activity associated with this contract was the purchase of a LeCroy 3500 transient recorder system with the $30,000 in equipment funds which was provided by ONR during this period. The LeCroy transient recording system was delivered in November, 1983. The software required to analyze plasma diagnostic data from Langmuir probes, retarding potential energy analyzers, and charge exchange neutral energy analyzers was developed between November 1983, and June, 1984 by Mr. Saeid Shariati. It is anticipated that this LeCroy system will not only give all the research assistants in the UTK Plasma Science Laboratory the opportunity to familiarize themselves with state-of-the-art data handling technology, but it also will also greatly speed up and increase the precision of our experimental measurements.

It is proposed to extend the research performed under this contract for a period of 3 years at the essentially the same level of effort. The proposal contemplates supporting the Principal Investigator for one quarter time, and 2 half-time research assistants in the UTK Plasma Science Laboratory. The funding required to accomplish this would be $69,658 for federal fiscal year 1985,

beginning October 1, 1984; $74,896 for FY 1986 and $84,882 for FY 1987. The total funding required over a period of 3 years would be $229,436.

The proposed research program over the next 3 years would focus on several interesting phenomena which became apparent during the exploratory investigations of the past several years. These include studies of fluctuations, turbulence, and propagating waves in the modified Penning discharge, using the analog-to-digital data handling system which has been developed under the Air Force contract; the use of sophisticated, active RF diagnostic techniques to measure the effective collision frequency and anomalous resistivity of the highly turbulent plasmas in these electric field dominated discharges; the use of specially calibrated, broadband antennas to measure quantitatively the RF power and microwave power emitted from these discharges as a function of plasma parameters; and further quantitative investigations of the geometric mean emission frequency and its dependence on the plasma parameters, including the plasma ion mass and the background cold plasma number density.

The proposed research program will be greatly assisted by sophisticated, state-of-the-art diagnostic equipment which we will be able to purchase as the result of an AFOSR, DOE-University Research Instrumentation Program grant of $233,000, which will become available after October 1, 1984. These funds will be used in part to purchase an RF network analyzer which will be useful in the active microwave diagnostic procedures contemplated to measure the effective collision frequency and anomalous resistivity of the plasma.

ONE-YEAR RENEWAL PROPOSAL

AND STATUS REPORT

for contract

N00014-80-C-0063

For the Period

October 1, 1987 to September 30, 1988

Prof. J. Reece Roth
Principal Investigator
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Knoxville, Tennessee 37996-2100

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This document describes a one-year extension to an ongoing program of research at the University of Tennessee's Plasma Science Laboratory, which is affiliated with the Electrica Engineering Department on the Knoxville campus. This program builds on a strong history of research in electric field dominated, steady-state plasmas. These plasmas exhibit several unique characteristics; very high levels of plasma turbulence; broad-band radio frequency emission; ion kinetic temperatures up to several kilovolts, higher than that of the electro population; and strong axial and radial electric fields, measured values of which have been in excess of several hundred volts per centimeter along the magnetic field. The presence of strong electric fields in the plasma allows work from external sources to be done on the plasma, thus affecting its confinement, heating, and transport properties. Such electric field dominated plasmas can achieve high energy densities, and are of potential utility in applications requiring high power densities, such as lasers, pulsed broadband radio frequency emitters, high power sub-millimeter micorwave emission, communications, and directed

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One-Year Renewal Proposal for the Period
October 1, 1987 to September 30, 1988

and

Status Report for the Period
October 1, 1984 to March 31, 1987

for

ONR Contract N00014-80-C-0063

Submitted to

THE OFFICE OF NAVAL RESEARCH

PHYSICAL SCIENCES DIVISION

by

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UTK Plasma Science Laboratory
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Coordinator

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EXECUTIVE SUMMARY

Background Information

This section describes the results of the first 2 1/2 years of our current 3-year ONR program of research at the University of Tennessee's Plasma Science Laboratory. Our laboratory is located on the Knoxville campus, and is affiliated with the Electrical and Computer Engineering Department. We specialize in the experimental investigation of interactions between RF radiation and plasmas, and on research in electric field dominated, steady-state plasmas. These plasmas exhibit several unique characteristics: very high levels of plasma turbulence; broad-band radio frequency emission; ion kinetic temperatures up to several kilovolts; ion kinetic temperatures much higher than that of the electron population; and strong axial and radial electric fields, measured values of which have been in excess of several hundred volts per centimeter along the magnetic field. The presence of strong electric fields in the plasma allows work from external sources to be done on the plasma, thus affecting its confinement, heating, and transport properties. Such electric field dominated plasmas can achieve high energy densities, and are of potential utility in such applications as lasers, pulsed broad-band radio frequency emitters, high power sub-millimeter microwave emission, communications, and directed energy weapons.

The current contract covers a three year period in one year increments, which extend from October 1 through September 30 of the following year. The contract support the Principal Investigator for 1/4 time during its entire duration. It also supported two graduate research assistants. The total budget of the contract over the current three-year period was $229,436, an

amount which supported the 16 archival and conference presentations listed in Appendices D and F, and suppported in whole or in part four graduate experimental theses at the UTK Plasma Science Laboratory.

Objectives of Research

The initial objective of this contract was to experimentally identify and confirm the existence of the geometric mean interpenetrating beam plasma instability in a classical Penning discharge, and to further explore the radio frequency emissions from this steady state, electric field dominated plasma. As the contract progressed beyond its first year, exploratory research with the diagnostic instruments available in the UTK Plasma Science Laboratory revealed additional interesting phenomena, the study of which was incorporated into the current three year research program.

The objectives of the research during the initial two years were to set up, with ONR support, a modified Penning discharge in the UTK Plasma Science Laboratory, and then to identify and confirm the existence of the geometric mean plasma oscillation in the steady-state, electric field dominated plasma. The geometric mean emission frequency was discovered jointly by Professors J. Reece Roth and Igor Alexeff of the UTK Plasma Science Laboratory. These objectives were met by the end of the second year of the contract. Exploratory research during the second year of the contract revealed broadband plasma turbulence in the modified Penning discharge. Strong axial and radial electric fields also were observed.

We studied the strength and nature of the broadband emissions from the modified Penning discharge; the interactions of microwave radiation with the Penning discharge plasma; the drift waves and turbulence observed in the plasma using time series analysis techniques; and we attempt to understand the anomalously high electrical resistivity observed in this plasma.

Recent Technical Results

During the first year of this three-year contract, a steady state, electric field dominated modified Penning discharge plasma facility was used. This facility, was recently altered to a uniform-field, steady-state classical Penning discharge operating with a water cooled magnet system capable of 0.4 tesla. Prior to the inception of the three-year contract, diagnostic systems were put into operation which included spectrum analyzers to examine RF emissions up to 28 GHz, and a retarding potential energy analyzer. The plasma is capable of operating for hours at a time and was observed to exhibit a broad-band RF white-noise spectrum over frequencies from 0.5 MHz to 1.0 GHz. The discharge was also observed to produce ions with characteristic energies, along the magnetic field lines, of several hundred electron volts, and the discharge also exhibited evidence of strong electric fields, up to several hundred volts per centimeter, along the magnetic field in the plasma.

During the first year of this contract, additional dignostic systems were placed into service, including a high voltage Langmuir probing system for axial profile measurements, and an active RF diagnostic system to measure plasma number density by observing the absorbtion of RF power at the

ele-tron plasma frequency. Phenomena investigated during this period included RF emission at frequencies over the band from 0.5 MHz to 2 GHz; ion energies and ion energy distribution functions; axial electrostatic potential profiles; and a rich variety of nonlinear mode coupling phenomena among the various RF, near-field emissions from the plasma.

During this contract, additional diagnostic systems were placed into service, which included specially made, broad-band antennae for the measurement of absolute RF emission levels over frequencies from approximately 50 MHz to 1200 MHz; a 32 GHz microwave scattering apparatus for the detection and study of plasma density fluctuations; and a two channel, analog-to-digital data handling system capable of measuring fluctuating phenomena up to 10 MHz, with associated software capable of obtaining auto and cross power spectra, phase spectra, and coherency spectra at frequencies up to 10 MHz. The two-channel data handling system was used to compare the density fluctuation signals obtained from the microwave scattering experiment with the fluctuating electrostatic potentials from a Langmuir probe on the plasma edge. This data handling system was also used to compare the fluctuating electrostatic signals from two capacitive probes located at different azimuthal or axial positions with respect to the plasma. The plasma fluctuation measurements made with the microwave scattering apparatus and the capacitive probes indicate a low frequency disturbance, in the range of 10 to 50 KHz in the plasma. This frequency is far too low to be associated with the ion or electron cyclotron frequency, or the Alfven velocity in this plasma.

During this contract, more detailed investigations of the broad-band RF emissions, from below 1 MHz to more than 2 GHz, were conducted. These emissions were found to be incoherent; the emitted radiation intensity was proportional to the electron number density and not to its square. A calibrated, broadband antenna was developed which had a flat frequency response from approximately 100 MHz to 1.2 GHz. Measurements made with this antenna showed that the efficiency of generating the RF emissions was only about 0.1%, and decreased with increasing plasma number density.

A theoretical program was undertaken to look in more detail at the theory of interpenetrating electron beams. This theory describes the geometric mean emission frequency, which is related to the high levels of electrostatic turbulence in the plasma. This theory was extended by Prof. Igor Alexeff and the Principal Investigator to include the effects of a cold background plasma in the region in which the two interpenetrating beams interact.

The experimental program during the past year of research also produced some very interesting and significant results. An active mircrowave plasma diagnostic procedure, which utilized the Hewlett Packard microwave network analyzer bought with the AFOSR URIP funding, was developed under our ONR contract, and applied to the plasma in the classical (uniform axial field) Penning discharge. This diagnostic procedure allowed us, for the first time, to measure the <u>effective collision frequency</u> in the classical Penning discharge plasma. It was found that, at low magnetic fields, below approximately 0.25 Tesla, the effective collision frequency in the classical Penning discharge plasma was approximately 0.5 MHz, a value consistent

with electron-neutral impact collisions in the plasma containment volume. At higher magnetic fields, however, the effective collision frequency increased dramatically, to values approaching 20 MHz, as the magnetic induction approached values of 0.4 Tesla. This increase in the effective collision frequency is associated with increased levels of turbulence in the plasma, which scattered the electrons more effectively than electron-neutral collisions.

Results of Other Contract Programs

Our AFOSR contract helped to support various activities in aid of our experimental and theoretical research program for the ONR. A major initiative in recent years of the AFOSR contract was a collaborative arrangement in computational physics with Dr. Robert J. Barker of AFOSR. The AFOSR contract was used as a vehicle to enable Dr. Barker to purchase the computer hardware and software required for this collaborative activity. This computer hardware, which includes an IBM AT computer with all peripheral equipment needed for computational plasma physics, was replaced by more up-to-date equipment and will be returned to UTK in the summer of 1987, where it will be available to support ONR computational physics activity.

Another activity was the purchase of equipment, including low frequency and high frequency (microwave) network analyzers, with $233,745 of fiscal year 1985 funds which UTK was given by AFOSR under the Department of Defense-University Research Instrumentation Program

(URIP). This equipment is also available to support the ONR contract. Another activity was participation by the Principal Investigator in the International Conference on Plasma Physics, held during the early summer of 1984 in Lausanne, Switzerland. An archival paper describing research done under this AFOSR contract was presented at this meeting and is included in Appendix D and E. An extensive trip report was submitted to ONR, which described technical developments at the conference, and the Principal Investigator's visits to European plasma-related laboratories before and after these conferences.

Finally, during the past two years of the AFOSR contract, it was used as a vehicle for a pilot program to support undergraduate students as research Fellows affiliated with AFOSR contract research in the UTK Plasma Science Laboratory. Six students were hired under this pilot program during the summer of 1985, and 10 in 1986. The program was extremely successful in terms of furthering the research objectives of our contract, and introducing engineering students to ongoing experimental research programs in the Plasma Laboratory. The ONR contract also benefited from the efforts of these summer students.

Utility of Results to the Navy

The steady-state electric-field dominated Penning discharge may be a test bed to study physical processes that occur in weapons-related intense microwave radiation and particle beam sources which are pulsed time scales to short to allow ready investigation of their physics. The observation of

broad-band, white-noise like RF emission over frequencies from 0.5 MHz to 2 GHz, was suggestive that this manifestation of the two interpenetrating beam instability might be useful for jamming communications, or for electromagnetic noise genertation. Indeed, the emissions from the Penning discharge plasmas in the UTK Plasma Science Laboratory were capable, under the right conditions, of jamming both AM and FM radio reception in Ferris Hall, where the Electrical and Computer Engineering Department and the Plasma Lab are housed. Quantitative measurements undertaken for this contract indicated that the intensity of the RF emisson was proportional to the electron number density rather than to the electron number density squared. This is characteristic of an incoherent radiation process in which each electron radiates power independently, rather than a collective, dipole-like emission in which intensity is proportional to the square of the number of electrons participating. Moreover, the overall efficiency of the emission process, defined as the integrated RF power divided by the dc input power to the Penning discharge, was on the order of 0.1% or less, and had a functional dependence such that the emitted power decreased with increasing plasma density.

Other results of this program may be of utility to future Navy programs. The production and maintenance of steady state, high power density plasmas for such military objectives as weapons effects, high power lasers, and directed energy weapons may benefit from our observation and level of understanding of anomalous plasma resistivity due to plasma turbulence. During this experimental program, radial and axial profile measurements were made of the electrostatic potential, number density, and electron temperature of the modified (mirror magnetic field along axis) Penning discharge. It was found

that, under highly turbulent plasma conditions, axial electric fields, parallel to the magnetic field lines, were as high as several hundred volts per centimeter in this plasma. The implied electrical conductivity of these plasmas is anomalous, and is several hundred to several tens of thousands of times higher than the conductivity to be expected from binary collisional processes.

APPENDIX J

Trip Reports Prepared Under ONR Contract ONR N00014-80-C-0063

THE UNIVERSITY OF TENNESSEE

COLLEGE OF ENGINEERING
Department of Electrical Engineering
Knoxville, Tennessee 37916

M E M O R A N D U M

TO: Thomas A. Bryant, Administrative Contracting Officer

FROM: J. Reece Roth, Principal Investigator, Contract N00014-80-C-0063

DATE: 24 May 1982

SUBJECT: Trip report on IEEE International Conference on Plasma Science, Ottawa, Canada

---

I attended the International Conference on Plasma Science, held May 17-19, 1982 in Ottawa, Canada. I presented two papers whicn were supported in part by ONR contract N00014-80-C-0063. Abstracts of these two papers are attached to this trip report, and I can provide copies of the slides used in the presentation (both were oral rather than poster papers) to those who are interested.

Among the co-sponsors for this conference were Carleton University and the National Research Council of Canada. There were approximately 400 papers presented at this meeting, and the number of registrants was more than 500. Most of the attendees were housed in the Carleton University dormitories, and the classroom facilities of the University were used for oral and poster sessions. Like previous conferences in this series, this conference spanned an unusually wide range of applied plasma-related topics. There were several sessions on laser-plasma interactions, intense electron and ion beams, magnetic fusion, commercial arcs and lighting devices, plasma diagnostics, and basic plasma physics research. Perhaps because the conference was held in Canada this year, there was an unusually large representation of overseas authors, particularly from Japan and Latin America.

One of the most active topics at this meeting was high power microwave and submillimeter wave generation, where a number of national laboratories and universities are working, on gyrotrons. Prof. Igor Alexeff of UTK presented a paper on his millimeter "Orbitron" microwave emitter, which attracted a great deal of attention, since it was one of the few new approaches to generating such radiation. This device creates millimeter microwave emission from electrons radiating as they spiral in toward a positively charged wire. They have successfully streched the pulse length of microwave radiation from this device from 20 microseconds to 5 milliseconds.

A new area which appeared at this conference for the first time, was rail guns and mass accelerators. This session was chaired by William Kerslake of the NASA Lewis Research Center in Cleveland, Ohio, and the results of several recent experiments were reported. It seems that the acceleration of projectiles to very high velocities is of interest in at least three distinct areas. The military are interested in projectiles ranging from 10 grams to 10's of kilograms and velocities up to approximately 4 kilometers per second. According to Kerslake, NASA is interested in the electro-magnetic launching of tons of matter (he suggested nuclear waste as a possible payload) to velocities comparable to escape velocity from the earth, 20 kilometers per second. A third area in which mass accelerators can find application is fusion research, where fusion grade plasmas must be re-fueled with pellets of deuterium and/or tritium weighing on the order of 1 to several grams, and which need to be accelerated to velocities between 1 and 10 kilometers per second, in order to carry the neutral fuel to the center of a burning fusion plasma.

Apparently a key result in this area is the Rashleigh-Marshall experiment in Australia, in which three grams were accelerated to a velocity of 5.9 kilometers per second, by a rail gun in which the acceleration was on the order of 600,000 gravities. Also at this session, the first fruits of an experiment at the Westinghouse Research Labs in Pittsburgh were reported. This experiment consists of a 17.5 megajoule homopolar generator set, which can provide 108 volts and up to 2.1 megaamperes to a rail gun configuration which can operate either with a plasma arc or a solid armature. That experiment has produced accelerations of 2.36 x 10^5 Gs, and while using a solid armature, has accelerated 300 grams to a velocity of 3, and 4.2 kilometers per second, in two initial experiments.

There was a sense of excitement at this session because these initial experiments appeared to demonstrate that the attainment of such very high projectile velocities was possible, and also because it appeared that this approach would meet a perceived need for high velocity projectiles in the fields of space, military, and fusion energy.

The session on plasma waves, instabilities, and antennas in which I presented my work had a number of interesting papers, including two invited Canadian papers relating to plasma experiments in space, and the propagation of plasma waves and instabilities in the magnetosphere. My paper on a paired comparison of high frequency rf emission from two configurations of electric field dominated plasma attracted interest, particularly my observation that the rf emission spectrum from the modified Penning discharge, which is being operated for the ONR contract, was capable of producing a white noise spectrum of rf emissions from below 1 megahertz to frequencies in excess of 1 gigahertz. The physical mechanisem of this white noise emission is presently obscure, but the observations in the laboratory have been quite clear. There also was interest in the tentative observation in these experiments that the modified Penning discharge (which has a large axial gradient of magnetic field to simulate magnetospheric plasmas) appears to have relatively large

longitudinal as well as transverse electric fields, on the order of tens to hundreds of volts per centimeter, while the classical Penning discharge operated under our AFOSR contract, appears to have, relatively, much lower longitudinal magnetic fields as a result of the uniform axial magnetic field strength.

In the controlled fusion area, there were a number of interesting new results, particularly from the German Wendelstein VII Stellarator experiment, and from the EBT-S experiment at Oak Ridge. It seems that the confinement properties of the Wendelstein VII Stellarator are superior to those of a Tokamak of comparable dimensions and magnetic field strength. In the EBT-S experiment, recent observations of 20 kilowatts of ICRH heating have resulted in significant increases in the number density (a factor of 2) and ion kinetic temperature (about 40% higher) in the relativistic hot electron rings which are thought to stabilize the plasma. These observations call into serious question the current theoretical understanding of the scaling of EBT plasmas. It is clear from these data that the hot electrons are not being lost by nonadiabatic effects (otherwise an increase in electron kinetic temperature would not lead to an increase in number density), and therefore renders invalid the nonadiabatic loss scaling arguments which were used to extrapolate from the current EBT-S experiment to the EBT-P and reactor grade plasmas. In addition, these observations are inconsistent with currently understood energy transfer processes, since it is not clear how 20 kilowatts of ICRH power into the ion population can increase the number density and kinetic temperature of the hot electron rings, which are absorbing approximately 200 kilowatts of ECRH power in these experiments.

Another fusion-related area of interest at this meeting was the Canadian tokamak program. The Canadian government has very recently approved a thirty million dollar, five year program to build a tokamak at the Hydro-Quebec Research Institute outside Montreal. This tokamak will be of about the general size and configuration of the ISX tokamak at Oak Ridge, but will be designed with special provisions which may allow continuous operation. They hope to do this by operating the ohmic heating current in an ac manner, and to keep the plasma hot enough and dense enough that they can reverse the ohmic heating current in a periodic manner. The Canadians are hoping, but cannot demonstrate, that the current penetration processes in the plasma will allow them to reverse the ohmic heating current in the plasma without destabilizing the plasma in the process. They are designing the vacuum vessel and ohmic heating coils in such a way that the current reversal will be possible within a few milliseconds. The operation of a tokamak with a periodically reversing ohmic heating current is hoped to be Canada's unique contribution to tokamak research and the world fusion effort. As I remarked to Claude Richard, head of this program at Hydro-Quebec, if this works, they will be heros; if it doesn't work nobody will be surprised.

On Wednesday morning there were a series of papers on plasma focus devices (in conflict with the session on railguns and mass accelerators). Two papers on the subject from Romania were withdrawn because the authors did not show up for the meeting. There was an interesting paper under AFOSR sponsorship

by Glenn Gerdin of the University of Illinois who reported a scaling law for the neutron production in a plasma focus device. It was found that the neutron yield scales as the current flowing to the plasma focus raised to the 4.6 power. Apparently in an earlier work, Dr. Gerdin reported charged particle energies resulting from plasma focus heating that exhibited energy distribution functions which were power laws, that is, the number of charged particles in a unit energy interval varied as an inverse high power of the energy. This is just the kind of energy spectrum that is observed in cosmic rays and other astrophysical plasmas where the energies of the particles are extremely high, and apparently due to violent heating processes.

TRIP REPORT

M E M O R A N D U M

TO: Dr. Michael A. Stroscio, Program Manager, AFOSR

FROM: Dr. J. Reece Roth, Principal Investigator, Contract AFOSR-81-0093.

DATE: 15 July, 1982

SUBJECT: Trip Report on the 1982 International Conference on Plasma Physics, Goteborg, Sweden, and Related Travel.

The Air Force Office of Scientific Research, Bolling Air Force Base, supported my participation in the 1982 International Conference on Plasma Physics, held in Goteborg, Sweden, June 9-15, 1982, where I reported on AFOSR sponsored research. A quirk in the airlines pricing policy allowed me to stay overseas for 2 weeks about $500 more cheaply than it would have cost to come back after 1 week at the end of the conference. I used the additional week to attend and give a paper at the Symposium on New Trends in Unconventional Approaches to Magnetic Fusion, which was held in Stockholm on June 16-18, 1982, and to stop at the Culham Laboratory near Oxford, England, on Monday, June 21st, where I renewed acquaintance with several of my collegues, gave a seminar, and had an opportunity to visit the site of the JET (Joint European Torus) experiment. My time overseas extended from June 8, to June 22.

The Goteborg conference was the second joint conference of the Kiev International Conference on Plasma Theory, and the International Congress on Waves and Instabilities. This was the fifth occasion on which the latter two conferences met, and the second time which they have met jointly. The conference appears to have been a great success. 36 countries were represented, with an unusually heavy representation of scientists from the USSR and Eastern Europe. There appeared to be unusually few no-shows among the Soviet block scientists. This participation was probably facilitated by the association of this conference with the Kiev conference, and the fact that it was held in a neutral country. There were about 36 countries represented at this meeting, 450 scientific papers were presented in parallel sessions, and at least 500 individual scientists attended the meeting. Once we arrived at the meeting site, the meeting turned out to have been very well organized, with all scientific and informal sessions appearing to go smoothly.

The United States was well represented at this conference, and almost every big name in US plasma physics was there. A rumor floated around the conference that the Nobel Prize Committee in Physics wishes to honor other branches of physics than high energy and solid state, such as plasma physics.

Representatives of this Committee were said to be in the audience, looking over some of the invited speakers who are candidates for a Nobel Prize in the plasma-fusion energy area. Hence, we heard invited talks by Marshall Rosenbluth, Richard Post, Harold Furth, and leading contenders for the Nobel Prize from other countries including the USSR. Most of the universities, national labs, and industrial organizations from the United States were represented at this meeting, but the Oak Ridge National Laboratory was conspicuous by its absence. Only two individuals from ORNL participated in this meeting, and they presented contributed papers. One of the ORNL representatives remarked that this conference had not been well publicized within ORNL, and that attendance was discouraged by the lab policy of withholding final permission to attend conferences until a few days before they were scheduled to leave. Thus, this individual received approval to attend on the Friday before he was scheduled to leave on a Monday!

For those who wish more detailed information about the conference, I have an outline of the sessions of the conference, a participant list, and a Proceedings volume, which contains papers describing the work presented at the meeting.

The opening session of the conference at 9:00 Wednesday was held with the customary European flair for pomp and ceremony. There were flowers on the stage. The welcoming address was made by the Chairman of the International Organizing Committee of the Conference, Professor Hans Wilhelmsson, who outlined the history of this conference and its evolution from the Kiev Conference and the Congress on Waves and Instabilities in Plasmas. He also emphasized the restriction of this conference to hot plasmas, wherever found, as opposed to gaseous discharge plasmas. We then had a short speech by Professor Kai Siegbahn, President of the International Union of Pure and Applied Physics. He attempted to put this meeting in the context of international physics research. He pointed out that there are approximately 10,000 plasma physicists in the world community, of which about 2,500 are in the USA. We then had a short speech by Dr. Alan Gibson, who is Chairman of the Plasma Physics Division of the European Physical Society. He welcomed everyone on behalf of the EPS, one of the sponsors of this meeting, and made the point that the importance of such a meeting as this was to get everyone out of the narrow molds of our individual fields of effort. Finally, we had a short speech by King Carl Gustaf of Sweden, who formally opened the conference with a short welcoming speech in which he expressed his awareness of the world energy problem and the importance of high temperature plasma physics and fusion energy in its solution.

MAJOR DEVELOPMENTS

The technical sessions of the conference opened with invited plenary papers by two of the grand old men of plasma physics, both of whom took the opportunity to announce/encourage major paradigm shifts in the understanding of plasmas. D. ter Haar of the UK spoke on the physics of hot plasmas. He contrasted the state of plasma theory now as opposed to that at the first Kiev Conference on Plasma Theory in 1971. One of the major trends which he identified was the growing interest in, and understanding of, plasma turbulence. In his discussion, he distinguished between fast and slow oscillations, associated respectively with electron and ion characteristic frequencies. He discussed the cascading of energy in frequency space, up or down the turbulence spectrum. He posed a question to the audience, that is yet to be determined, as to what extent ordinary fluid turbulence is a guide to the understanding of plasma turbulence. He suggested that the proper small parameter for plasma turbulence theory was the quantity which can be though of as the ratio of the electrostatic pressure to the plasma pressure,

$$\varepsilon^2 = \frac{\varepsilon_0 E^2}{2nkT} \ll 1$$

The inverse of this quantity would be the electrostatic analog of the plasma instability index beta, familiar from magnetic confinement theory. Ter Harr's emphasis on the importance of plasma turbulence to understanding the behavior of hot plasmas was good to hear, and exactly coincided with my own views on the subject. Many of the possible future directions of research which he mentioned in his talk are ones which are part of the program here at the UTK Plasma Science Laboratory.

The second invited talk was by Hannes Alfven, the only living Nobel Prize winner in plasma physics, who spoke on "Paradigm Transition in Cosmical Plasma Physics". In this talk, Alfven discussed the changes in our basis of understanding cosmical plasmas (and by extension, of hot plasmas in general) from the older macroscopic fluid description, to the more nearly correct kinetic or individual particle description. The latter has come into increasing use since 1960, and has made possible a correct understanding of many phenomena which are only qualitatively or incorrectly understood by the older fluid theory. An interesting aspect of Alfven's position is that his textbook Cosmical Electrodynamics was the seminal reference for the older fluid theory. Since winning his Nobel Prize about 10 years ago, Alfven has attempted to hasten this paradigm shift. He pointed out that the kinetic approach has resulted in a complete change in the basis for understanding magnetospheric plasmas. He remarked that the fluid theory first collapsed in the field of fusion energy, then in the theory of the magnetosphere, and is now in serious trouble as a theoretical approach to understanding large-scale astrophysical phenomena such as interstellar clouds. He pointed out that electric double layers in the magnetosphere, which have been observed by satellites and which were a major topic at this conference, could not be properly understood by a fluid theory, but were correctly described by the kinetic or single particle approach. Another matter that was of concern to Alfven was an aspect of the old fluid MHD theory in which magnetic field lines were regarded as being frozen into conducting fluids. He took full blame for having introduced

that concept into astrophysical theory, and pointed out that it should now be laid to rest,

There were two major "buzz-words" or hot topics at this meeting. These were "electric double layers", and "magnetic field line reconnection". A double layer is a structure which can arise in a flowing, magnetized plasma as a solution to the kinetic equations, and which will permit a parallel electric field to develop along an externally imposed magnetic field. The electric field is a reuslt of the Poisson equation, and is sustained by two regions (or a double layer) of charge, one positive and one negative, which maintain the parallel electric field between them. These structures have been observed in the magnetosphere, and more recently in laboratory plasmas. The concept of the double layer has been around for at least 20 years, but it was only very recently, and even at this conference, that their existence could be said to have been widely accepted. There were a remarkably large number of theoretical and experimental papers on electric double layers, which was probably reinforced by a three-day workshop on the subject held in Sweden at the close of this conference.

The concept of magnetic field line reconnection got quite a bit of play, both in an astrophysical context (solar flares) and in the context of fusion energy (spheromak production, compact tori formation). Magnetic field line reconnection looks like the last gasp of the old fluid MHD theories, and occurs when two regions containing hot plasma and with oppositely directed magnetic fields contact each other. When this happens, the magnetic energy stored in the magnetic fields is fed into the plasma and heats it to produce a solar flare or other similar phenomena. Magnetic field line reconnection occurs in Marshall-type plasma guns, railgun accelerators with plasma armatures, spheromak production, etc. When these structures are formed, the forces acting on the plasma usually stretch out the magnetic field lines embedded in the plasma as well as the plasma itself, until the plasma, in being hurled away from the fixed source, reaches the "breaking point". The magnetic field lines are pictured as reconnecting to each other within the plasma and disconnecting from the source.

An interesting major development in the field of fusion energy was a new physical process for achieving a steady-state current drive for toroidal devices, like the tokamak, that required a toroidal current for stability. One of the most serious drawbacks of the tokamak concept for powerplant fusion reactors is the fact that it in principle is a cyclic device, in view of the natural tendency of the ohmic heating current in the toroidal direction to dissipate through Ohmic heating of the plasma. A very clever mechanism to sustain this toroidal current in toroidal plasmas was put forward by John Dawson of UCLA. He suggested that the electron drift velocity in the toroidal direction could be maintained by synchrotron radiation pressure. When the electrons in a fusion plasma exceed about 30 keV, enough synchrotron radiation is produced by the plasma to have a significant effect on the energy and momentum balance of the plasma. It was suggested by Dawson that the plasma be surrounded, around the minor circumference, by annular mirrors and absorbers, arranged in a "fish scale" pattern, such that all of the synchrotron radiation circulating around one sense of rotation in the toroidal direction is absorbed, and all radiation circulating in the opposite sense is reflected. This preferential absorption of synchrotron radiation would then preferentially impart momentum to the electron population producing this radiation, and drive currents around

the torus. Dawson presented calculations which indicate that for 30 to 50 keV electron temperatures, fusion plasmas may produce enough radiation reaction force on the electrons to sustain ohmic heating currents of a magnitude required for fusion reactors.

A final major development which emerged at this conference was a proposal made by a Harold Furth et al. of Princeton to control fusion reaction rates by controlling the degree of polarization of the fusionable fuel nuclei. It seems that by proper fueling techniques, it is possible to polarize the light element nuclei that are to undergo fusion reactions, with respect to the confining magnetic field. Once the nuclei are polarized, this places constraints on the types of reaction which those nuclei will undergo. By properly arranging the polarization between the nuclei of deuterium and tritium, for example, it should be possible to enhance the reactivity of the DT reaction by a factor of 1.5 above the published values. An even more intriguing possibility may exist in the case of the DD reaction. Here, if the polarization of the two nuclei have the proper relation to each other, it is possible to almost completely supress the neutron-producing branch of the DD reaction, while enhancing the tritium branch. This therefore may be a mechanism to burn deuterium, while supressing neutrons produced by the primary reaction.

The biggest uncertainty with this concept is whether or not the nuclei will remain in a fixed state of polarization throughout the scattering collisions and other randomizing processes which the fuel of a fusion reactor would normally experience. Harold Furth and his co-authors on this paper have done calculations which seem to indicate that the forces which would depolarize the nuclei in a fusion plasma are sufficiently weak that the depolarization time is longer than the particle confinement time required for a Lawson reactor. If this holds up, it could be a major development in fusion energy, since it would allow one to burn naturally available deuterium without producing intense neutron fluxes and without the necessity of breeding tritium.

OTHER INTERESTING DEVELOPMENTS

Peter J. Barrett from the University of Natal, South Africa gave an experimental paper on turbulent heating in a cross-field ion beam experiment, which ties in well with some work we have done at the UTK Plasma Science Laboratory, and reported at the same meeting. In his experiment, a 27 centimeter diameter beam of argon ions with energies of about 40 eV were generated. The ion beam was neutralized, and then traveled perpendicular to a relatively weak magnetic field, less than 80 gauss. The magnetic field did not significantly affect the trajectory of the ions, but the electrons were tied to the field lines. The argon ions were approximately monenergetic, and the plasma noise levels were quite low. Barrett had a retarding potential energy analyzer which measured the energy distribution function of the ions. This was nearly monoenergetic at low levels of plasma turbulence. As the noise level in the plasma increased, however, the spread of ion energies greatly increased. This result was not too surprising by itself, but Barrett was able to show that the rate at which the ions were heated increased like the 4th root of the noise level for low levels of noise, and was directly proportional to the noise level at high noise levels. In our experiments at UTK, we do not start with a clean-cut monoenergetic ion distribution function as did Barrett, but we also have observed spreading of the ion distribution function, and increasing levels of thermalization with increasing levels of rf emission and plasma noise. Barrett, in his experiments, had not made any attempt to observe rf emissions at the same time he was making these energy spreading measurements.

Harold Furth of Princeton gave an invited talk describing some recent results at Princeton, mostly on the PLT. He reported that the increase in ion kinetic temperature in the PLT plasma was a direct function of the neutral beam input power per confined particle, and that this curve was a straight line which did not saturate even at the highest densities and power inputs which they had achieved thus far. This was a very encouraging result, particularly in view of early fears that large amounts of neutral beam heating power might destabilize the plasma as a result of trapped particle instabilities. At Princeton they produced a plot of temperature increase versus power input per particle for both ion cyclotron resonance heating and neutral beam injection. At the same power input per confined particle, ion cyclotron resonance heating was more efficient than neutral beam injection, and led to a larger increase in the kinetic temperature.

In both the PLT and PDX experiments at Princeton, they have achieved values of the plasma stability index, beta, up to about 3%, and then have difficulty with instabilities above that level. This is a rather low value for power reactors, for which they would like to have somewhere between 5 and 10%. In the PDX experiments, when they plot beta versus the input power, the relationship is linear and there is no saturation, which would indicate instability.

During his paper Harold Furth made the interesting admission that they do not understand particle and energy transport in tokamaks. This had been obvious for ten years, but it is only recently that they have felt able to say this publicly, since funding for construction of their large tokamaks is already committed! In addition to their major tokamaks, they are building the spheromak, a device for producing independent blobs of plasma

which will resemble ball lightning, but with energy densities of fusion interest. They are also studying a magnetic containment configuration called HELIAC, which consists of helical stellarator windings, with a current carrying conductor on the magnetic axis. This configuration should be stable to betas of at least 25%. The drift surfaces of this configuration have cross sections which look like crescents or bananas, which twist helicaly like thick vines around the center conductor of the configuration.

Richard Post of Livermore gave an invited talk on the physics of mirror systems, in which he reviewed the early history of magnetic mirrors, and then went on to discuss current work at Livermore on tandem mirrors. He pointed out that electrostatic containment was essential in mirrors in order to have adequate containment time for net fusion power production. The ambipolar potentials which result in ion trapping he suggested were controlled by the Boltzmann (barometric) equation, and also by "pumping", the preferential addition or removal of charges by means of ECRH heating or the injection of neutral beams. In the discussion after his paper Post agreed that the Boltzmann equation is a poor theoretical basis for describing the electrostatic potential well in tandem mirror plasmas, since it assumes a statistical-mechanical equilibrium plasma, and all mirror plasmas are very far from kinetic or statistical-mechanical equilibrium. He mentioned that Cohen at Livermore is trying to account for the effect on ambipolar potentials of species-specific escape cone angles.

R. J. Bickerton described the JET (Joint European Torus) scientific program. I will describe more of this in connection with my site visit to JET, but Bickerton pointed out that the dominant aim of JET was to achieve as rapidly as possible a plasma with conditions and dimensions approaching that of a fusion reactor. Indeed, JET is much larger than the TFTR, and very nearly as the INTOR and/or FED reactors. Table I gives a set of parameters for JET and the INTOR reactor, taken from a slide presented by Bickerton. They are hoping to get their first plasma in JET sometime in June or July of 1983, and they intend to operate for their first year with ohmic heating only. They have designed JET to operate after 1985 with 10 megawatts of neutral beam injection, and 15 megawatts of ion cyclotron resonance heating. The neutral beam injection power will be applied first, and then the ion cyclotron resonance heating will be installed on and after 1985. Bickerton stated explicitly that it was not their aim to understand tokamak physics. In the discussion period he admitted that European electric utilities are not at all aware of the situation in fusion research. An interesting aspect of the JET design is that it does not have a divertor of any kind.

This paper was followed by a paper by Engelmann from the Netherlands on the physics requirements for a tokamak engineering test reactor. The tokamak engineering test reactor is the European equivalent ofthe fusion engineering device (FED) in the United States. This is intended to be something beyond the INTOR generation of reactor and would be, if it ever comes to fruition, a European project.

There was an interesting paper on fractal analysis of power spectra by S. Johnson of the USA, in which he applied topological theorems to plasma turbulence in a way that seemed totally devoid of physical insight or information about physical processes. There also was a paper on computer

TABLE I

DEVICE	MAJOR RADIUS R	MINOR RADIUS a	VERTICAL ELONGATION $k = h/a$	ASPECT RATIO R/a	MAGNETIC FIELD, B_o TESLA	OHMIC HEATING CURRENT I,MA
JET	3	1.25	1.6	2.4	3.5	5.0
INTOR	5.2	1.20	1.6	4.4	5.5	6.4

DEVICE	SAFETY FACTOR q	FLAT-TOP DURATION T	AVERAGE DENSITY n, M^3	ION TEMPERATURE T_i, keV	$\beta(\%)$	β_p	τ_E, SECONDS
JET	2.9	13 SEC	9×10^{19}	7	4.4	1.4	1.0
INTOR	1.9	∞	1.4×10^{20}	10	3.9	1.6	1.4

simulation of plasma turbulence in open systems by Yu. S. Sigov of the USSR, who attributed many aphysical results in this field to the imposition of periodic boundary conditions and the requirement of fixed total energy in the system, since most real systems have large energy inputs that maintain the high levels of turbulence of interest.

Russel M. Kulsrud of Princeton gave an invited talk on plasmas in astrophysics in which he discussed magnetic reconnection and collisionless interactions, all the time using the older and by now discredited MHD and frozen-in field line models. He proceeded to discuss these two phenomena in the context of a wide variety of astrophysical observations, most of it, in my judgement, being simply hand-waving which made no quantitative predictions, and much of which would not stand up if analyzed on the basis of kinetic theory arguments. In discussion, he was asked about the validity of this older MHD model, and admitted that his approach was valid only for very large-scale phenomena, at and beyond the scale size of interstellar distances. Ravi Sudan of Cornell gave an interesting talk on the spectra of magnetic field fluctuations in a turbulent fluid, in which he attempted to tie plasma turbulence to the large body of information on classic fluid dynamic turbulence. He used mixing length theory to establish a time scale based on the eddy turn-over time, the fluid velocity, and a characteristic scale size of the phenomena.

Bruno Coppiof MIT gave a paper on the near-term feasibility of advanced fuel fusion reactors, in which he recognized my recent contributions in this area. He made the point that it would be very desirable to demonstrate the near-term feasibility of advanced fuel fusion reactors and pointed out some of the economic, social, and engineering difficulties associated with developing the DT fusion fuel cycle, particularly in the low-beta tokamak configuration. He proposed to develop high-beta tokamak experiments in which deuterium and tritium would be used for start-up by ohmic heating alone, and then the plasma would be allowed to run away thermally to high kinetic temperatures which would allow them to bleed in helium-3 and fuel the reactor with deuterium and helium-3. He discussed a small size, high beta D^3He tokamak based on the Alcator-C called CANDOR, which would generate a total fusion power output of 100 megawatts, of which 53 megawatts would be thermal power, 33 bremsstrahlung, 10 megawatts in synchrotron radiation, and 4 megawatts of neutron production.

I next attended a session of contributed papers, most of which dealt with turbulence and astrophysical plasmas. Many of these papers were attempts to analyze satellite data, which were interpreted as various maifestations of plasma turbulence. It would seem that the field of magnetospheric or astrophysical plasma turbulence is significantly behind the state of understanding and data base that has been developed in recent years in fusion research and/or high temperature laboratory plasma research, as inadequate as the latter is.

E. Mazzucato from Princeton gave an interesting paper on recent observations on microturbulence in the PLT tokamak. They looked at the spectrum of small scale density fluctuations in the PLT in an attempt to understand the radial transport processes. They concluded that transport in the PLT tokamak remains completely mysterious. The ions appear to behave classically insofar as their transport of energy is concerned, but the electrons do not. They apparently have no idea what physical process is responsible for anomalous transport in the PLT tokamak. They have

found that drift wave transport processes do not scale properly to explain the observations. Significantly, they have observed plasma rotation, with a frequency between 1 and 2 kilohertz. He remarked that this could be due to a radial electric field if the plasma in the PLT had a negative floating potential. This drift velocity reverses when they reverse the direction of the toroidal magnetic field. They find a total voltage drop across the radius of about 1500 volts over a radial distance of about 30 centimeters. This gives rise to a radial electric field on the order of 50 volts per centimeter in the ohmically heated tokamak. When they attempt to look at the electric potential fluctuations with energetic neutral injection, they find that when they apply more than about 3 megawatts of neutral beam injection power, there is so much turbulence their instrumentation is saturated and cannot measure it. Under these conditions, they do not know the electron energy containment time in the plasma and they do not accurately know the amount of power deposited in the plasma.

In a post-deadline paper, H. Berk of the University of Texas at Austin gave a paper on the MHD stability of EBT plasma. This paper was extremely disappointing. The basic approach was the old fluid MHD analysis, and completely left out of consideration radial eelctric fields. Electric fields ranging from 10 to 50 volts per centimeter are known to exist in the EBT plasma, so there is really no excuse for pursuing a theory which neglects them, and Berk admitted as much in the question period after his paper.

Marshall Rosenbluth gave a major invited paper on plasma instabilities, in which he spent about the first half-hour reviewing the current status of instability research for fusion applications. Interestingly, he defined micro-instabilities to be those instabilities which have an electric field parallel to the magnetic field. He spent the second half of his review lecture describing some recent work on the stability of tandem mirrors, which indicates that tandem mirrors may have a low frequency MHD instability as a result of the region of unfavorable curvature in the central portion of the mirror.

Forrest Jobes of Princeton gave a talk on current drive on the PLT experiment. They operate with lower hybrid heating and feed the RF into the plasma with a waveguide array. They showed a photograph of the waveguide array in operation at a level of several megawatts, and at that point there was no sparking visible-a common problem in RF heating of this type. They were able to sustain current with a zero loop voltage for a period of 1 second, and the coupling was best at number densities between 2 and 4 x 10^{12} particles per cubic centimeter. The efficiency of the current drive dropped drastically above densities of about 6 x 10^{12} particles per cubic centimeter. A high density limit may exist for RF current drive, and may be a serious limitation of this method. In addition to sustaining the ohmic heating current for 1 second with no loop voltage around the torus, they actually increased the ohmic heating current and the electron number density with the RF current drive.

Tsytovich from Russia gave a paper entitled "A New Mode Coupling Process in Plasma Turbulence", which was a replacement for a paper with the same title by Dr. Nambu, a Japanese. He discussed extensively the application

of Kirchoff's emission law in turbulent plasmas, and described the conditions under which a turbulent plasma can be optically thick at the electron cyclotron frequency. An interesting aspect of this talk is that Tsytovich referred to a gamma-ray laser which he called the GASER (Gaze-er). This is the first time I heard anyone mention this acronym, or the gamma-ray laser. The connection between the gamma-ray laser and his talk on plasma turbulence was not at all clear, although he did seem to imply that plasma turbulence was somehow involved in the gamma-ray laser, as if somehow an energetic, turbulent plasma could be stimulated to act like a laser at gamma-ray frequencies.

On the last day of the conference, a Japanese, Yamanaka, spoke on inertial confinement fusion, and described laser fusion research underway at Osaka, Japan. He described some pellet configurations that I had not seen discussed before, including what he called the foam and double-shell targets. The foam target consists of a DT pellet at the center surrounded by an annular shell of foam material, the function of which apparently was to rapidly ionize and absorb the laser radiation. The double shell foam target consists of a DT pellet at the center surrounded by an annular shell of foam, and then an outer hard shell outside the foam. He also described something called the "cannonball" model which was a double shell target with a hole in the outer shell. The laser radiation apparently comes in through the hole in the outer shell, and reflects in the annular cavity. He claimed a six-times enhancement of the compression over a uniformly compressed target. He claimed to have gotten pressures of 30 megabars in these experiments.

REPORT ON THE SYMPOSIUM ON NEW TRENDS IN UNCONVENTIONAL APPROACHES TO MAGNETIC FUSION

This symposium was organized by Bo Lehnert of the Royal Institute of Technology in Stockholm Sweden, and took place on June 16-18, 1982. Its timing was arranged to dovetail with the Goteborg conference. Eighty-three individuals attended this conference. There were 27 papers with no simultaneous sessions. I had a paper on the program entitled "Ion Heating and Containment in an Electric Field Bumpy Torus (EFBT) Plasma". This paper summarized work on the EFBT concept which I had done at NASA Lewis.

This conference was not well advertised in the United States, and so the program and attendance was dominated by Europeans who were interested in so-called "unconventional" approaches. Here in the United States, the stellarator/torsatron group at Wisconsin, the Topolotron group at Brigham Young University, the Tormac group at Berkeley, the Linus effort at the Naval Research Laboratory, and several others were not represented on the program. Most of these papers were neither new nor unconventional. Many of the papers were concerned with various types of pinches, including reversed field pinches, field reversed theta pinches, theta pinches, Z-pinches, and other variations of the basic pinch concept. There seemed to be little concern that these concepts would make poor fusion reactors from an engineering point of view. Except for my own paper and that of Quinn, no one discussed the engineering requirements that need to be placed on advanced fusion reactors. I was very pleased with the reception of my own paper on the EFBT concept. Sixty copies of the paper were picked up from the registration desk, and I had several interested questions after my presentation. The proceedings of this Symposium are going to appear as a separate issue of the Journal of Nuclear Instruments and Methods sometime during the next year.

An invited paper on the reversed field pinch was given by H. A. D. Bodin of the Culham Laboratory, who is a pioneer in this general area. The reversed field pinch (RFP) goes back to the old ZETA experiment operated at Harwell in the late 1950's. In RFP's, the toroidal and poloidal components of the magnetic field are of comparable strength (unlike tokamaks, where the toroidal field is about a factor of 10 stronger), and in the outer regions of the plasma the toroidal magnetic field has the opposite direction (ie. is reversed) with respect to the magnetic field on the axis. The RFP radial equilibrium is produced by the plasma itself, which sustains the required RFP configuration by a process known as self-reversal. Since the current in RFP's can exceed the Kruskal-Shafranov limit, there is powerful ohmic heating. Because of the high shear of the magnetic field lines along the radius, confinement at high beta may be possible. In the RFP, the current does not flow around the major circumference of the containment volume like a simple single-turn loop; the current configuration actually looks like a thick rope wound around the magnetic axis in a helical spiral.

In RFP's an important parameter is the ratio of the total plasma current to the number density of the plasma. When this parameter is high, the plasmas of RFP's are plagued by impurities and have a high Z_{eff}. The scaling of the energy containment time is not neoclassical but under characteristic operating conditions the energy containment time in RFP's

is approximately 10% of the classical energy containment time. These energy containment times are approximately 1/10 to 1/50th of the energy containment times predicted by Alcator scaling. Typical values of the energy containment time in RFP's range from 30 to 300 microseconds, and values of the plasma stability index beta are typically 10%. At this stage of RFP research it is not clear what physical process limits the value of beta, but it seems that values of beta up to 25% may be possible with larger devices.

The Ohmically Heated Toroidal Experiment (OHTE), one version of which is in operation at General Atomic in San Diego, is a cross between the stellarator and the reversed field pinch. The pulse lengths of OHTE experiments range from 1 to 10 milliseconds, with a value of the plasma stability index beta that is typically 10%. Number densities are in the range of 1 to 10 x 10^{13} particles per cubic centimeter. Although there are about 5 OHTE experiments currently in operation, we heard in detail about the one from General Atomic. They claimed to have achieved a plasma with minimal impurities, and a Z_{eff} of approximately unity. The plasma stability index for the poloidal field component was about 30% for the OHTE experiment, and only about 10% when this experiment was operated in the RFP configuration.

Harold Furth presented an invited paper on Compact Tori, nearly all of which was devoted to the spheromak configuration. He distinguished between the field reversed theta pinch, in which the toroidal magnetic field is zero, and the spheromak configuration in which a strong poloidal magnetic field is assisted by a toroidal magnetic field in the plasma. The spheromak is a freely moving plasma blob of a kind originally developed by Wells, although Furth did not give Wells credit during his talk. The spheromak plasmas should be stable for extended periods of time, and may be related to the phenomenon of ball lightning, which, in some instances, has been observed to be stable for periods of 30 seconds or more.

They have conducted a series of preliminary experiments at Princeton which generated small spheromak plasmas. They are currently building the S-1 experiment, which was preceeded by the proto S1,-S2-S3, which operated with slightly different magnetic field configurations. At Princeton, they expect the average beta in spheromak plasmas to range between 5 and 10%, and they feel that spheromak plasmas may be capable of values of beta as high as 30 or 40%. The spheromak concept has serious defects from an engineering point of view, including the pulsed or cyclic nature of the plasma, and the rather small size to which the spheromak plasmas appear to be limited. However, Furth made the point that the magnetic field at the coils generating the spheromak plasma is less than the magnetic field within the plasma itself. This is opposite from a tokamak, where the toroidal magnetic field in the plasma is significantly less than the magnetic field in the coils.

I presented a paper for George Miley on "Conmpact Tori for Alternate Fuel Fusion", since George could not make the conference due to a personal emergency. George made the assumption that a reversed field theta pinch could be operated in the steady-state by neutral beam injection and a form of curren+ drive, then proceeded to examine some of the engineering implications of the reversed field theta pinch. George Miley has been an advocate of the reversed field theta pinch for several years, even at a time when workers at the Los Alamos National Laboratory were not taking

him seriously. George Miley concluded that a reversed field theta pinch should make an attractive engineering test facility for advanced fusion fuel cycles. Such a facility would generate only a few tens of megawatts, while still providing fluences and other fusion burn conditions appropriate to reactor conditions.

A paper by W. E. Quinn from Los Alamos described their experimental work on compact toroids, which includes the CTX facility (compact toroidal experiment). They use a coaxial plasma gun to produce the compact toroid, and they observed the magnetic reconnection which leads to the separation of the compact toroid from the coaxial source. The compact toroid is characterized by an electron density of 2 to 4 x 10^{14} particles per cubic centimeter, an electron temperature of 10 eV, a peak magnetic field trapped in the plasma of 6 kilogauss, and total configuration lifetimes up to about 0.7 millisecond. They also have a second facility, the Field Reversed Configuration (FRC) which is a high beta, axisymmetric compact toroid that is prolate i.e. stretched out along the axis of the plasma. In this device, the containment times are on the order of .1 milliseconds, the electron number densities from 2 to 5 x 10^{15} particles per cubic centimeter, electron temperatures are 200 to 500 electron volts, and the value of the plasma stability index, beta, about .7 to 1.0.

One of the newest and most interesting of the experiments reported at this meeting was the "Rotamak" experiment, which is being operated at the Flinders University of South Australia. This configuration consists of a plasma confined by a strong vertical magnetic field. Superimposed on this is a transverse magnetic field which rotates in a plane normal to the vertical magnetic field. Typical rotational velocities are on the order of several hundred kilohertz. The values of beta achieved in this experiment approach unity, with confinement times that so far are relatively low, on the order of a few 10's of microseconds. The electron number densities of this plasma have been as high as 10^{14} particles per cubic centimeter. Most of the limitations of the parameters reported in this paper are clearly the result of the rather small scale of the experiment, and the investigators are quite confident that more interesting results will be possible when the experiment is scaled up.

Professor Arnulf Schluter from Garching, West Germany, gave an invited talk on advanced stellarators. He has been one of the leading advocates in Europe of the stellarator configuration, and has worked closely with the Wendelstein VII experiment at Garching, which is currently the world's largest stellarator experiment. They have achieved a plasma stability index beta of 1% in their plasmas, and he feels that stellarators should be capable of operating with betas as high as 5%. They are currently building a scaled-up version of the Wedelstein VII experiment, which will use existing toroidal field coils, but will not have the usual helical stellarator windings wrapped around the containment volume. Instead of these helical windings, the Wendelstein 7-AS experiment will have modular, twisted coils, which will generate the same magnetic field configuration as an $\ell = 3$ helical winding, but which can be removed independently and do not contain conductors that thread the toroidal field coils. This will be a major experiment, and they intend to apply ion cyclotron heating, neutral beam injection, electron cyclotron resonance heating, and ohmic heating to the new version. They have looked at a fusion reactor scale-up of this device, which would have a beta somewhat under 5%. The

stellarator is capable of operating in the steady-state, unlike the classical tokamak, but the beta limitation means that from a practical engineering point of view it cannot be used to burn advanced fusion fuels.

A very impressive paper was presented by Professor Koji Uo from Kyoto University in Japan. The eliotron-E is an $\ell = 2$ torsatron configuration made up of modular field coils which produce a plasma with an elliptical cross-section. This experiment is also a very large one. The modular coils are water-cooled copper, the major radius of the experiment is 2.2 meters, and the minor radii of the plasma is 21 and 40 centimeters, since the plasma cross section is elliptical. The toroidal magnetic field of this experiment is 2 Telsa. Professor Uo presented a very impressive set of diagnostic data, much more extensive and complete even than major tokamak experiments in the West, which showed time histories of radial profiles of various plasma parameters. The particle and energy containment times achieved in this configuration are impressive. The electron energy containment time has been up to 35 milliseconds, and the Lawson parameter (ie the product of density and energy containment time) has been has high as 2.5×10^{12} seconds per cubic centimeter. The ion kinetic temperatures during neutral beam injection have been up to 660 electron volts, with about 500 electron volts of this kinetic temperature being due to the neutral beam heating. They have seen no sign of saturation of the ion kinetic temperature as a function of the input power. The number densities are typically 3×10^{13} electrons per cubic centimeter and the particle containment time has been as high as 70 milliseconds. They have injected up to 1.3 megawatts of neutral beam power in this experiment and Professor Uo expects that the plasma stability index may be as high as 5% in reactor-sized devices. This device should in principle be capable of operating in the steady-state, but it was disappointing that, like tokamaks and stellarators, its stability is apparently limited to betas of no more than about 5%.

There were several papers on Z-pinches from the Los Alamos National Laboratory, Japan, and the Imperial College of Science and Technology in London. The Z-pinches are high density experiments, which involve as much as 10 million amperes of current flowing along the axis of the discharge. This current generates a self magnetic field which pinches the plasma to a small diameter. The electron number densities range from 5×10^{19} to 10^{21} particles per cubic centimeter. The duration of these experiments is extremely short, and while they are a useful test bed for high density plasma physics, it is not at all clear how they can be translated into a reactor that is efficient and feasible from an engineering point of view. This feasibility problem was not addressed in any of the papers at this conference.

A paper was presented by S. C. Prager of the University of Wisconsin on high beta multipoles. This configuration is generated by four levitated rings inside a toroidal chamber with an approximately square minor cross section. The plasma is confined mostly in the region between the four conducting rings which are spaced in the shape of a square in the minor toroidal cross section. This approach is one which will almost certainly not lead to a power producing reactor because of the necessity of having the levitated rings in the containment volume. Such rings would be heated or destroyed by the power flux from a reactor plasma. Nonetheless, Prager made the point that multipoles are useful because

neoclassical theory is virtually identical in all symmetric toroids including tokamaks, spheromaks and multipoles. They observed the so called Bootstrap current which arises from the diffusion of particles across the magnetic field. The bootstrap current occurs along the magnetic field. They claimed that their measurements agree with neoclassical theory. These multipoles are capable of very high beta, and they have experimentally observed values of beta ranging from 11% to 44% at a characteristic location in their containment volume. The value of beta of 11% is consistent with MHD stability theory, but the higher limits, 44%, are claimed to be above these predicted by MHD instability theory.

John Dawson of UCLA gave an interesting paper on a toroidal confinement experiment which features direct ohmic heating of the ions. This is a toroidal version of the picket fence concept, in which the magnetic field is generated by magnetic polepices on the wall of the containment vessel, and the magnetic field lines then bow inward toward the toroidal containment vessel. The plasma is established in the low magnetic field region. Since the device is toroidal the electrons tend to be trapped on magnetic field lines. When an ohmic heating current is driven by transformer action, the induced current is carried by the ions, since they are not trapped on the magnetic field lines. They found that a toroidal ion current of 3 to 6 thousand amperes results, and they verified that the current is carried by the ions. The ion temperatures are 40 to 110 eV in a plasma with a density of about 10^{13} particles per cubic centimeter. The electron temperature is lower and is generally in the range of 20 to 40 electron volts. The beta of the plasma high, about 20 to 30%. This is a rather interesting device, since the magnetic field is stronger at the coils than it is in the containment volume. This is also an attractive possibility for advanced fuel cycles, which may be operated at high kinetic temperatures where synchrotron radiation from hot electrons can be a problem in strong magnetic fields. They proposed to build a larger device with a major radius of 90 centimeters, a minor plasma radius of 30 centimeters, a magnetic field of 1 tesla at the cusps on the wall. They expect in this device to get an ion kinetic temperature of 1 keV.

Al Wong of UCLA gave a paper on "Surface Magnetic Confinement in Toroidal and Linear Mirror Systems." These devices also have magnetic poles generated by electromagnets or permanent magnets on the wall of the vacuum vessel, which form a magnetic field configuration weak at the center of the containment volume and which increases as one approaches the walls. In one of these devices they achieved a particle containment time of about 100 milliseconds, and a Lawson parameter as high as 7×10^{10} seconds per cubic centimeter. At UCLA, they recently built a new device called LAMEX (Large Axisymmetric Mirror Experiment) in which the parameters span the range 10^9 to 10^{13} particles per cubic centimeter and ion temperatures from 1 to 100 electron volts. They conducted experiments to determine the mirror ratio scaling. It appears that the containment time varies at least linearly with mirror ratio, the ratio of maximum to minimum magnetic fields in this device, rather than with the logarithm of the mirror ratio, as is the case with 90° scattering collisions.

There was a very interesting paper by D. D. Ryutov from the Institute of Nuclear Physics in Novosibirsk, USSR. The mirror research at Novosibirsk does not often get published in the literature. In this invited paper,

Ryutov described the work at his Institute, one major thread of which is research on simple axisymmetric magnetic mirrors. He seemed to advocate the use of simple magnetic mirrors, rather than tandem mirrors. Ryutov seemed to feel that the tandem mirror concept had at least two important defects. He expected that microinstabilities would result in fast scattering of confined particles into the escape cone, and he felt that there was an unacceptable constraint on the allowable level of microfluctuations, since such fluctuations would lead to loss in the escape cone. This was a rather interesting point of view since the tandem mirror concept originated in Russia. He described a series of rotating plasma experiments, similar to the old Burnout-V experiments which were operated at Oak Ridge. These are based on a device simialr to the modified Penning discharge, in which a strong magnetic mirror provides gross confinement, and the plasma is biased with electrodes at either end so that a strong radial electric field points radially outward. This leads to $\bar{E} \times \bar{B}/B^2$ rotation of the plasma. The centrifugal force thus produced improves the longitudinal confinement.

He made the interesting statement that the E/B drift velocity should be about 2 to 3 times the ion thermal velocity. I'm not sure why he thought so, since in my own work I showed that the drift velocity and the thermal velocity are comparable in a modified Penning discharge. The number densities that have been achieved are on
ticles per cubic centimeter in the PSP-I device, which operated over 1971-1979. This had a pulse duration of 10 milliseconds. Ion kinetic temperatures of 1 keV were observed, with electron kinetic temperatures of 20 eV. This large ratio between ion and electron kinetic temperatures is a result of both species achieving essentially the same drift velocity, so that their energies tend to be proportional to the masses. The magnetic mirror had 1 tesla in the magnetic mirror throats, and a 2 1/2 to 1 mirror ratio. They followed the PSP-1 device with a second, huge upgrade of it, the PSP-II, which was built one year ago and has just recently gone into operation. This machine is about 4 meters high and 15 meters long. The maximum magnetic field is 7.2 tesla, and it has a 2.5 to 1 mirror ratio.

In addition, Ryutov described some work with electrostatically plugged cusps, a very old idea which the Russians are still pursuing, and which they regard in many ways better than the tandem mirror since the electric fields are externally imposed. He cited as the main problem the large size of the so called "point cusps" at the magnetic field maximum, and the difficulty in blocking the cusps with electric fields imposed by electrodes.

In addition to the above experiments at Ryutov's Institute, they are also building the GOL-3 experiment, which is a multiple-mirror experiment with 30 individual magnetic mirrors in a linear array. One would think that they would have been better off to have made these into a bumpy torus, but the principle of operation of this device is that the individual magnetic mirrors are to have a mean free path for scattering into the escape cone that is comparable to the length of the individual mirrors. Under these circumstances, an ion which scatters into the escape cone in one of the central mirrors will have a high probability of being scattered back into the confinement region of velcity space when it traverses one of the other mirrors. This is a larger and scaled up version of the multiple

mirror system that was operated at Berkeley.

I have the conference Proceedings, but not as yet the full length papers, available in my office for anyone who wishes further information.

VISIT TO JET/CULHAM JUNE 21, 1982

On my way back to the United States, I stopped at the Culham Laboratory to visit with John Butterworth and his collegues in the Fusion Technology Group. While there, I also saw the JET experiment, which is in the final stages of assembly. I was suprised to find that fusion technology, as we understand it in this country, is very little emphasized at Culham. The Institute for Plasma Physics at Garching, West Germany appears to be the European lead center for fusion technology. This lack of emphasis at the Culham Laboratory was attributed to the fact that the previous director was a physicist, and not particularly interested in fusion technology. It is felt that that situation may change, since the current Director of Culham has a solid state physics background, and is well aware of the materials and other engineering problems facing the fusion community. I gave a seminar presentation on my recent work on wall loading limits and economic constraints on advanced fuel fusion reactors, and this seemed to be well received. In Culham, as in Europe generally, there seems to have been little thought or attention given to the needs of the electric utilities, to the constraints on fusion power imposed by enginering considerations, or to the advantages or disadvantages of advanced fusion fuel cycles relative to the DT reaction.

The JET (Joint European Torus) was very impressive. The original design of this experiment started in 1973, when a consensus among the fusion research laboratories in Europe was reached that the next step in fusion research was too large for any one European country to support it alone, and that this experiment would have to be a combined European effort. It was further agreed that the device should be a tokamak, although the politicians insisted that it be called a torus and not a tokamak, in case some other magnetic field configuration should prove more desirable from a technical point of view. The design team which produced the tokamak was convened as early as 1974, and was headed up by Rebut, the French engineer who built the successful TFR tokamak at Fontenay-Aux-Roses which went into operation in March of 1973. Because of his involvement as head of the design team, it is no coincidence that the technology of JET very closely resembles that of the TFR tokamak, and is fundamentally unlike the technology of the DITE or CLEO experiments at Culham. The latter, for example, use liquid nitrogen temperature toroidal field coils. The JET project encountered delay between 1975 and 1977, during which time the design team almost disbanded. This delay was almost solely on the single issue of siting the experiment. The European Council of Ministers appointed an advisory committee consisting of senior scientists from various European labs and asked them for recommendations on several points, including siting the people who were technically qualified, however, refused to give the politicians a recommendation on which site should be chosen.

The politicians temporized for 2 years until a consensus emerged that the experiment should be sited at the Culham laboratory in England. National sensitivities required quite a bit of horse-trading among the various countries supporting this experiment. The site is located in England, the head of the design team is a Frenchman, and the man responsible for building the JET experiment itself, Hans-Otto Wuster, is a German. Moreover, it was agreed at the time JET was sited at Culham that any successor to it would not be located in England. The JET experiment was a precedent-

setting effort of scientific cooperation for the common market countries, and the political aspects of this have been summarized in a book by Denis Willson, entitled "A European Experiment". It makes interesting reading for anyone involved in the management of scientific experiments.

One aspect of the JET experiment is that the scientists responsible for it seem to have gotten away with murder in terms of setting themselves easily achieved goals for the operation of the experiment. Achieving scientific breakeven or any other form of fusion energy breakeven is not one of the goals of this experiment, and hence they feel free to operate the JET device with ordinary hydrogen from its inception in mid-1983, until sometime in 1988 or beyond. Only at that time will they burn deuterium and tritium. There is no requirement that the fusion power produced be equal to the input power, or any other number. The goals of the JET experiment are rather vague; they are that the device will extend the parameter range of tokamaks, that the scaling of plasma parameters will be tested, that the technology of operating large fusion experiments will be developed, and so forth. The formal goals of the experiment look easy to achieve and may be achieved very soon after the experiment is first turned on.

The JET experiment is housed in a separate part of the Culham Laboratory with its own shops, office building, motor-generater hall, etc. The office buildings and working environment is superb. The European politicians apparently did not quibble about the funding of the buildings. The lounges, conference rooms, individual offices, and beautifully landscaped gardens will be very attractive to staff from all over Europe. The control room of the JET is very advanced from a human factors point of view. It was pointed out that there are no buttons to push or knobs to turn anywhere in the control room. All of the control functions will be handled by typewriter keyboards and interactive video displays.

The JET apparatus itself is located in the "torus hall" which is a huge structure with concrete walls about 3 meters thick, to shield against the production of neutrons. The entire structure will be operated as a containment vessel at a slightly negative pressure, to contain any tritium. At one end of the torus hall is the assembly hall, which is not a hot cell. There is an intermediate room between the experimental bay and the assembly hall with 3 meter thick doors on it which can serve as a hot cell for the dissassembly of any components that are activated in the experiment. The cross section of the JET plasma is very large, and D-shaped. The aspect ratio is relatively small, about 2.5 to 1. All together, the JET is much larger, and appears to be much better engineered than the TFTR at Princeton. Moreover, the JET seems to have been designed with a sounder sense of physics priorities. For example, the JET experiment will be capable of operating between 20 and 30 seconds at maximum magnetic field, whereas the TFTR experiment was designed with such limited magnetic field capability that it can operate only 1/2 second at maximum magnetic field. The longer containment times possible in the JET experiment could make a very significant difference, if the containment times for either particles or energy scale up to be longer than a few seconds. Also, the long pulse times possible in JET may make it possible to examine the scaling of the ohmic heating decay time, which may not be equal to the value suggested by Spitzer conductivity, but something more rapid, due to anomalous resistivity.

TRIP REPORT TO THE 18th INTERNATIONAL CONFERENCE ON PHENOMENA IN IONIZED GASES

Swansea, Wales
July 13-17, 1987

by

J. Reece Roth
ONR contract N00014-80-C-0063
AFOSR contract 86-0100

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FORWARD

This report describes the 18th International Conference on Phenomena in Ionized Gases, which was held in Swansea, Wales, July 13-17, 1987. Two representatives of the UTK Plasma Science Laboratory attended. Prof. J. Reece Roth was supported by AFOSR contract 86-0100 (Roth), and Mr. Paul D. Spence by ONR Contract N00014-80-C-0063.

TRIP REPORT ON THE 18TH INTERNATIONAL CONFERENCE ON PHENOMENA IN IONIZED GASES

The Conference and Its Antecedents

The International Conference on Phenomena in Ionized Gases, which was held from the 13th to to the 17th of July 1987, in Swansea, Wales, was the 18th in a series which began at Oxford in 1953. This conference has been held in various European countries every two years since that time. The scope of this conference excludes fusion related plasmas, high temperature plasmas, astrophysical plasmas, waves and instabilities in plasmas, and atomic collisional or ionization phenomena. The conference includes gaseous discharges and low temperature plasma physics, both theoretical and applied. English is the official language of the conference. The conference is managed by a 12-person international scientific committee, the members of which are each from different countries.

The scientific program of the conference features 45 minute general invited lectures which review a broad field of interest, of which there were eleven in the mornings of each day. The conference also featured 26 topical invited lectures of 30 minutes each which are presented in two parallel sessions in the afternoons of the conference. Finally, contributed papers were presented, all in poster format, during the afternoons of the conference. As in previous conferences the papers were submitted approximately 6 months before the conference date, reviewed, and published in the form of a four volume proceedings which was distributed to the participants as they

registered at the meeting. The invited papers will be published after the meeting and sent to the conference participants approximately 6 months after the conference.

Some statistics of the conference may be of interest, which illustrate its international character. There were 434 contributed poster papers at this meeting. There were approximately 550 participants at the conference, including 55 accompanying persons (spouses, etc.) from 33 countries. Among the national delegations, there were 93 individuals from the United Kingdom, of which 41 were not from the University of Wales in Swansea. The next largest delegation was from West Germany with 49 people. There were 46 participants from the USSR, 39 from France, 38 from Japan and 34 from the United States. Among a random selection of other countries, there were 17 participants from the Netherlands, 12 from Yugoslavia, 12 participants from Hungary, 11 from Poland, 9 from Australia, 8 from Italy, 5 from Canada, and 4 from mainland China. In most cases, these numbers are a fair reflection of the amount of low temperature plasma research and development in the respective countries. An exception is the United Kingdom, where approximately 50 of the 93 UK participants were from the University of Swansea, and many of these were not plasma physicists, but were graduate students or staff members who were helping with the organization and running of the conference. With 34 participants, the U.S.A. was definitely under-represented with respect to the amount of relevant plasma research going on in this country; this under-representation carried over into the invited and contributed papers as well, with few US researchers giving

features of the JET facility were explained to us. That Saturday happened to be a good time for such a tour, since the facility was not operating, and was opened up so that it could be inspected by members of the public, behind its shielding wall. There is no doubt that this facility is extremely well engineering and very impressive in its size and overall design. It is now fitted with both neutral beam injection and rf heating, and their experimental program is now experimenting with magnetic neutral points and magnetic divertors as a means of purifying the plasma (the JET plasma is extremely dirty by large fusion machine standards, with Z_{EFF} ranging between 2 and 5 for most of their runs). They have been unable to operate the JET facility in the H-mode when the magnetic neutral points and the magnetic divertors are on field lines whch are closer to the plasma than the material limiters or the walls.

invited papers, and many of the US participants at the conference not having contributed papers on the program.

The conference was held at the University College of Swansea of the University of Wales. The city of Swansea is on the southern coast of Wales, approximately halfway between the English border and the westernmost extremity of the Welsh peninsula. The University is located in a very attractive, park like campus. The logistical and social aspects of the conference were extremely well organized by the staff of the University College of Swansea. The scientific sessions ran morning and afternoon and were not carried over into the evenings, which were kept free for such cultural activities as a string quartet concert, Welsh folk dancing, a banquet at the Swansea Town Hall, and the conference banquet on Thursday evening. Wednesday afternoon was unscheduled and kept free for tours; the conference was completed by noon on Friday, thus allowing the participants an early start on their way home.

I personally found the contributed papers to be generally more interesting and of a higher standard than the invited papers. The general and invited lectures were often of very disappointing quality. Rather than the broad, integrative survey lecture that the audience had a right to expect, the invited speakers too often said at the beginning of their lecture that the topic which they had been invited to cover and which they had accepted an invitation to cover was too broad, and that they would specialize to a narrower scope, which included their own work and that of a very few others. Many of the invited lectures also were disappointing in being poorly researched, poorly organized, or having inadequate visual aids. Some clearly were prepared at

the last minute in the form of handwritten visual aids on transparencies provided by the conference secretariat. This tendency to waste the time of the audience on inadequate invited speakers has been a characteristic shortcoming of this conference for the entire time that I have been familiar with it (I first attended this series of conference in 1967). Part of the problem with the invited speakers probably is a reflection of the way in which the conference is run, by a 12 person international scientific committee containing only one representative from the US, West Germany, and Japan, three countries that are probably doing more than half the work in the field covered by the conference. In the closing ceremony, it was announced that Dr. Authur Guenther of the Air Force Weapons Lab, Kirtland Air Force Base, had been elected as the US representative to the International Scientific Committee.

Technical Overview of Conference

The last times that I attended this series of conferences was in 1967 in Vienna, Austria, and in 1969 in Bucharest, Romania. In the intervening years, when I have had support to attend international conferences, I have attended the conferences on Waves and Instabilities in Plasmas, since that conference was more relevant to my research interests. However, the failure of the Kiev International Conference on Plasma Physics this year left this conference as the most appropriate second choice. Being away from the conference for a period of 18 years allowed me to view this conference with a perspective different from those who have attended it regularly, and to better identify some significant changes which have occurred over that time. 20 years or so ago, the work reported at this conference was more basic, more academic, and more theoretical than the papers which were presented in Swansea this year. It was evident that there has been a sea change in the emphasis of research in this general area in all of the industrialized countries that were represented. The focus on low temperature plasmas and gaseous discharges has remained substantially the same. The change has been from theoretical, academic, and basic research to specific industrial and commercial applications, or to phenomena that have some identifiable application to commercial or military applications.

This shift in the emphasis of the conference from theoretical to applied manifest itself in several ways. For example, I have the definite impression that there were many more representatives at this conference from industrial laboratories (outside the US) than attended it 20 years ago. In addition, many topical areas which were of academic or theoretical interest and which were

well represented 20 years ago scarcely appeared on the program of this conference at all. An example of this is the interest in moving striations, propagating waves which are observed in the normal glow discharge at pressures on the order of 1 to 10 torr. These propagating waves represent one of the oldest problems in plasma physics, having been observed by Michael Faraday in the 1830's. In spite of much research over more than a century, there still does not exist a satisfactory theory to describe their behavior or dispersion relation. There were perhaps 20 or more papers on this subject in the conferences of 20 years ago, but at this conference there were no more than three or four. In fact, a center of moving striation research at the Institute of Plasma Physics in Prague, Czechoslovakia, did not have a representative at this conference. I would estimate that well over half of the papers were motivated by applications to lasers, to plasma processing of materials, or military applications involving the interaction of laser radiation with matter.

Survey of Selected Invited Papers

In this section, I will summarize those invited papers at the conference which I was able to attend. This included all of the general invited lectures given in the mornings, and nearly half of the topical invited lectures. The latter were scheduled in parallel, in the afternoon, in such a way that it was not possible to attend more than half of them. Full length versions of these invited papers are to be published 6-9 months after the conference.

On Monday morning, A. V. Phelps of the Joint Institute for Laboratory Astrophysics (JILA) in Boulder, presented a paper on discharges at extremely high values of E/N and low currents. The parameter E/N is more usually expressed as the ratio of the electric field in volts per centimeter to the

background neutral gas pressure in torr, p, and is a very important similarity parameter in low temperature gaseous discharges. Normally the electric field E is independent of discharge current up to about 10^{-4} amperes, and over the pressure range from 0.1 to 1 torr. In conventional low temperature gaseous discharges, the value of E/p might range up to perhaps 100 volts per centimeter-torr. By high values of E/p, Phelps had in mind values of several thousand to 10^4 volts per centimeter-torr. He discussed some of the physical phenomena that were characteristic of these high values of E/p, which in argon included excitation of forbidden lines by fast neutrals in the gas, and ionization by fast ions at values of E/p above several times 10^4 volts per centimeter-torr.

The second general invited lecture on Monday was given by Botticher from East Germany, who spoke on ionization kinetics in shock heated rare gases. The experimental work on which he reported was done in shock tubes with very high pressure ratios between the drivng and driven gas. His research looked very much like a resurgence of the shock tube work that was supported by the Department of Defense in the late 1950's and early 1960's, with one exception, and that was his accounting for non-maxwellian electron energy distributions.

On Monday afternoon F. Leuterer of the Max Planck Institute for Plasma Physics in Garching, West Germany gave a talk on current drive in the ASDEX tokamak with lower hybrid waves. I have summarized this talk in a later section of this trip report on the fusion related activities at this conference.

Also on Monday afternoon, K. Szego from Budapest, Hungary gave a talk on plasma phenomena around a comentary nucleus. This paper summarized European results from space probes that passed near Halley's comet. It was particularly interesting, inasmuch as the United States had no probe of its own for the measurements that were reported by Szego. This was virtually the first time that any kind of quantitative scientific measurements had been made by a space probe in the near vicinity of a comet. Much of the data were the first of their kind, and many unanticipated phenomena were observed. Traces of ice and bursts of heavy ions were observed by the space probe as far as 28 million kilometers away from the comet. As the probe approached to 7 or 8 million kilometers, hydromagnetic waves were observed in the magnetic field embedded in the interplanatery medium. The waves had very large ratios of the magnetic field fluctuation amplitude to the mean background value, which ranged from 20 to 50%. It was concluded that much energy was carried away from the bow shock of the comet by ion Alfven waves. Szego also remarked that particles seemed to be accelerated by stochastic mechanisms, including scattering on turbulent lenses of plasma, and they found that the particles became more isotropic as they approached the bow shock of the comet. This turbulent heating would seem to be similar to that which we are studying in the UTK Plasma Science Laboratory, and have observed in the modified Penning discharge experiment as part of our ONR contract.

Also on Monday afternoon, Hans Pecseli of the Riso National Laboratory in Denmark gave an invited talk on conditional eddies or clumps in ion beam driven turbulence. This paper was of great interest to Paul Spence and I, since

he has taken measurements on a Q- machine which are similar in kind to the active plasma turbulence measurements that Paul Spence and I have made on the modified Penning discharge recently for our ONR contract. Pecseli did selective sampling of data from two potential fluctuation time series taken from his Q- machine plasma. The selective data sampling consisted of digitally sampling signals with amplitudes above a threshold, in a way that simulates the kind of selective sampling that is done with an oscilloscope when one adjusts the trigger signal for the oscilloscope in such a way that only signals with a high initial amplitude are displayed. He reasoned that signals with relatively high amplitudes above a threshold would in some sense be more characteristic than the random or stochastic signals of lower amplitude. He found that, in his Q- machine, axial electrostatic potential wells form and propagate along the beam direction. This velocity was measured and was found to be less than the velocity of the beam ions in this experiment.

The amplitudes which he looked at were in the highest ten percentile of the fluctuating electrostatic potential signal in his plasma. He made the point that these axially propagating coherent structures were not too rare. As a whole, the physics of his Q-machine was somewhat different from our experiment at UTK, which does not have an axial ion beam in it. However, his time series analysis from two separate digitally sampled probes was very similar in general philosophy to ours. In addition, he discussed in a contributed paper the observation of azimuthally propagating rotating spokes, which were apparently driven by E/B drifts, and which resemble the strong radial spokes which are frequently observed in our modified Penning discharge at UTK.

Finally, Y. Nakamura from Japan presented a topical invited lecture on experiments on ion acoustic solitons in a multicomponent plasma with negative ions. The work which Nakamura presented was apparently motivated by practical applications to electrical switchgear, where negative ions play a role. His experimental arrangement put a high negative pulse on a grid which was located in the middle of a sulfur hexaflouride plasma at a pressure of 1 to 2 x 10^{-4} torr of argon, with the sulfur hexaflouride (the species which produced the negative ions) having a partial pressure that ranged up to 2 x 10^{-4} torr. He found that the negative sulfur hexaflouride ions gave negative solitons with a negative pulse on the grid in his plasma.

The first general invited lecture on Tuesday morning of the conference was by W. Witteman from the Netherlands, who gave a very interesting talk on excimer lasers. He characterized excimer lasers as operating between 120 and 640 nanometers, and containing such diatomic rare gases are Ar_2 and Xe_2, as well as chemical combinations of the rare gases with flourides or halides. The molecules used in excimer lasers are stable in an excited state but dissociate when a photon is emitted. The interest to this conference was that gaseous discharge plasmas are used to create excimer lasers, and the efficiency of pumping the lasers is a key issue that involves much gaseous discharge physics. In the kind of excimer laser he discussed, pre-ionization technology is important. They typically use high voltages and high currents produced by a one megavolt Marx generator. Their E-beam laser pump had a current rise time of 50 nanoseconds and produced a relativistic electron beam with a current density of 300 amperes per square centimeter. This device had a discharge efficiency less than 10% and typcially was in the range of 2 to

4.2%. Witteman stated that the experiment and theory were in good agreement in predicting the efficiency of the discharge. Some of the problems which they had in their experiment were in getting a homogeneous glow discharge which could be pumped by the relativistic electron beam. The background electron number density was about 10^7 electrons per cubic centimeter prior to the electron beam pulse, and was about 10^{14} electrons per cubic centimeter during the electron beam discharge. He remarked that microwave excitation of these excimer lasers did not appear to be useful because the electron energies are too low to excite the short wavelength lines of interest.

The second general invited lecture on Tuesday was given by A. H. Guenther of the Kirtland Air Force Base. Art Guenther gave a very well organized and well presented lecture on optical control of gaseous discharges, in which he surveyed the many fast switching techniques which have been developed by his AFOSR program at Kirtland, with emphasis on those that use optical control to initiate breakdown. He showed slides and data from the unclassified fast triggering system which has been developed for the PBFA-2 inertial fusion experiment at the Sandia Laboratories. He pointed that in this experiment, all 36 switches fired within two nanoseconds.

The third and final general invited lecture of Tuesday morning was by W. Ebeling of East Germany, who spoke on instabilities and phase transitions in dense hydrogen, rare gases and alkali plasmas. This was an interesting and highly mathematical presentation in which some of the classical methods of solid state physics and nonequilibrium thermodynamics were applied to dense plasmas. Ebeling felt that the methods which had been applied to

semiconductors could provide useful estimates of the effective diffusion coefficients in dense plasmas under conditions of high density, and large free energy densities. For specific mathematical results of Ebelings work, we will have to wait approximately 6 months until full length versions of the invited talks are published.

On Tuesday afternoon, Allen Rees of the University of Liverpool gave a topical invited lecture on plasma and plasma assisted processing of semiconductor materials. The work which he described was largely his own and was motivated by the application to integrated circuits. He pointed out that semiconductors must be etched to a scale of 1 micron or less, and that to assure reliability, the etching must not be damaged around the gate of the semiconductors, which is often smaller than 1 micron. He characterized typical plasmas used for plasma etching and which are generated by microwave power as having electron number densities of 5×10^{10} electrons per cubic centimeter. He also mentioned briefly the application of plasma processing to integrated optical electronic devices intended for fiber optic applications.

Although one of the disappointments of the conference was the absence from the program of any paper on recent developments in diamond deposition, there was an excellent general invited lecture on Wednesday morning by J. Perrin of the Ecole Polytechnic in France on the multidisciplinary task of plasma deposition studies; the growth of hydrogenated amorphous silicon induced by silane discharges. This invited paper described a process very closely related to the more interesting diamond deposition, the plasma assisted chemical vapor deposition processes which results in the growth of

very pure silicon by silane discharges. Silane is a compound of silicon and hydrogen, the chemical formula of which is SiH_4. When an rf discharge is made in this gas, under pressures which range from 10^{-4} to 1 torr and electron number densities from 10^4 to 10^{11} per cubic centimeter, very pure silicon can be deposited on surfaces in contact with the silane plasma. The deposition rates discussed by Perrin ranged from .01 to 10 angstroms per second. The percentage of ionization in these discharges is less than 0.1%, and the electron kinetic temperatures are quite low, ranging from 0.1 to 5 eV. The energy fluxes resulting from this deposition range from 0.01 to 1.0 watts per square centimeter. The overall impression given by Perrin's talk was of a relatively mature technology, with techniques well in hand for building up layers of very pure silicon and other materials.

The second general invited lecture, the last scheduled for Wednesday, was by A. S. Trubnikov and M. V. Nezlin from the Kurchatov Institute in Moscow, who presented a general invited lecture on analog simulation study of drift vortices (solitons) in plasmas and spiral structures. Trubnikov attended the conference and presented the paper. He made the point that solitons can determine transport processes in plasmas, including plasmas of thermonuclear interest, and are therefore well worth studying. With that brief initial remark, he cast loose completely from plasma applications with the comment that one could draw an analogy between water waves and plasma gradient drift waves. The analogy to the plasma drift waves that he discussed was a parabolic sheet of water maintained on the inner surface of a rotating axisymmetric parabolic cup. Surface waves on this parabolic sheet of water which were produced or modified by an external perturbation, were an

analogy to what can happen with gradient plasma drift waves of interest in fusion plasmas. Much of this talk was devoted to discussion of a movie of an actual experiment which was done with probably a few dollars worth of equipment, including a rotating parabolic cup on a turntable, with the parabolic surface of the water illuminated in such a way that surface waves and their perturbations could easily be seen. When the perturbation took the form of a latitude-like annular disk on the surface of the parabola, the resulting vortices looked cyclonic in character. Semi-permanent, soliton- like structures very reminescent of cyclones on the surface of the earth or the great red spot on Jupiter maintain themselves for relatively long periods of time. Under certain conditions, one could see stable, spiral-arm like structures which resemble the rotating spokes which develop in magnetrons, or in galactic spiral arms. The movie was a very interesting illustration of nonlinear fluid dynamics, but the connection to phenomena in plasmas was not clear, but may be made so in the published version of these invited talks.

The first general invited lecture of Thursday was presented by F. Weinberg of Imperial College, London, who spoke on combustion and plasmas. He mentioned that typical flames may have an electron number density of 10^{10} electrons per cubic centimeter, with typical ionic species in flames being OH^-, and HCO^+. In zero gravity, flames apparently are spherical, and one can direct flames in zero gravity by electric fields. He described flames as plasmas, ignition of flames by plasmas, and the use of plasma jets in combustors. In the latter two areas, he pointed out that such things as plasma jet spark plugs were developed for aircraft, and were found to be reliable. He pointed out that electrically augmented flames, that is plasma jets and

plasma torches, had a history that went back at least to 1924. According to Weinberg, interest in electrically augmented flames peaked in the 1960's and 1970's with the prospect of cheap nuclear electricity, but interest has receded in recent years when it appeared that this was not going to happen. He showed some very interesting and very elegant diagnostic data which were obtained by laser induced florescence of OH^- present in the flame that he was studying.

The second general invited lecture on Thursday was by M. I. Rabinovich from the Institute of Applied Physics in Gorky, Russia, who spoke on dynamical chaos in plasmas. This lecture was highly mathematical, and full appreciation of Rabinovich's point will have to wait for publication of his paper in the invited conference proceedings. He did claim to have demonstrated the random behavior of a strictly deterministic system which is relevant to plasmas. He showed us several phase plots which showed chaotic motions resulting from the dynamics of Langmuir solitons in plasmas. His mathematical approach appeared to be based on systems of first order, nonlienar Volterra equations, very reminescent of the approach published about 15 years ago by Mannheimer and Flynn of the Naval Research Laboratory, although Rabinovich's work has gone considerably further than theirs.

The first topical invited lecture which I attended on Thursday afternoon was by Yu. I. Ostrovskii, of the Ioffe Institute in Leningrad, who spoke on holographic interferometric diagnostics of plasmas. Perhaps the most interesting single feature of his talk was his willingness to commit himself to a quantitative measure of the sensitivity limit of this method of differential

density measurement, which was expressed in terms of the index of refraction of the plasma, the probing wavelength, the electron density, and the plasma thickness. He mentioned that high quality recording materials (by which he meant photographic plates) was a problem. The measurements which he showed us were taken on the tokamak AT-2.

Another interesting topical invited lecture on Thursday was by G. N. W. Kroesen of the Eindhoven University of Technology in the Netherlands, who spoke on possibilities and limitations of plasma deposition. This paper was concerned with a chronic problem in the field of plasma deposition and etching as applied to integrated circuits: measurement of the surface deposition rate as the etching or deposition process is occuring. He had some data on the transport process from the plasma glow discharge through the sheath to the surface. In his laboratory the deposition rate is measured by an unusually sophisticated form of in situ ellipsometry, which is an optical arrangement for studying the thickness thin films on solid surfaces. It relies on the fact that if plane polarized light is incident on a thin surface, it is reflected as elliptically polarized light. The degree of ellipticity in the reflected beam depends the thickness of the film, and thereby allows measurement of the film thickness as it is deposited by the plasma.

A change of pace in the topical invited lectures was provided by T. E. Allibone of the City University of London, who is in his late 70's or early 80's, and is still doing publishable research in the field of high voltage dc breakdown. According to Allibone, there has been a recent resurgence of interest in dc high voltage breakdown because of the use of extra high voltages by the electric utilities for long distance or under water power

transmission. He devoted his talk to some observations on the basic physics of dc breakdown in atmospheric air, an area in which apparently there is still much to be learned. He was able to make some new observations because the high voltage laboratory at the City University of London has no windows and it is possible there to watch the high voltage breakdown process in its entirity under very low levels of interfering background light. When two meter diameter spheres, charged to voltages between 1/2 and 1 megavolt dc, were observed in the dark with their surfaces sidelighted, the side illumination made evident dust particles which were drawn to the surface of the sphere where the electric field was highest. These dust particles stacked up into whisker-like structures, which finally became of such length that they broke loose from the surface and then traveled along electric field lines to the opposite electrode, where they received the opposite electrical charge, and continued to build up their length. These whiskers would slosh between the two electrodes in turn. Because the electrodes were spherical, and the electric field lines curved, they would walk away from the center line. These whiskers seemed to play a role in streamer formation and in the breakdown process. According to Allibone, the formation and disappearance of these streamers off to one side of the electrodes would continue until the dust of which they were formed was cleared away from the surface of the sphere. He attributed the well known fact that large spheres at megavolt potentials in air have to go through a conditioning process before they will hold off high voltages, to the formation and cleaning up of these whisker-like structures in the gap between the two spheres.

The conference finished at noon on Friday, during the morning of which there were only two general invited lectures. The first of these was by H. R. Greim of the University of Maryland, who spoke on Stark broadening and shifts of spectral lines in plasmas. This was an excellent tutorial and survey lecture on the subject, which I look forward to seeing in the printed conference proceedings. It started by reviewing material on Stark broadening which can be found in Greim's book on Plasma Spectroscopy, which is now at least 20 years old, and brought it up to date with recent data and techniques, particularly the active laser based plasma diagnostic methods.

The final general invited lecture of the conference was given by W. Englehardt of the JET Joint Undertaking at Culham, who gave a lecture on heating and confinement of plasmas in the JET tokamak. A discussion of this invited talk may be found in the section of the trip report on fusion related issues.

Survey of Selected Contributed Papers

There were too many contributed papers at this conference to comment on individually, or even grouped into the 18 subject areas used to organize the conference.

Three papers by H. L. Pecseli from Risco on pages 360, 362, and 368 of the Proceedings were of particular interest to us here at UTK. These papers reported more detail than Pecseli gave in his invited talk, on his experiments using digital time series analysis techniques to analyze the nature of fluctuations and turbulence in his plasma. In this Q-machine plasma, he was able to demonstrate the formaiton and long lifetime of E/B driven rotating spokes on the edge of the plasma. These spokes were formed by active

perturbation of a probe at the edge of the plasma, and consisted of vortex-like structures with an axial extent that covered almost the full length of the plasma. The quantity measured in Pecseli's experiment was the fluctuating electrostatic potential, measured with floating Langmuir probes. Some runs also were made in which density fluctuations were measured, under the assumption that the density fluctuations were proportional to fluctuations of the ion saturation current of a Langmuir probe. The Q-machine plasma studied by Pecseli was far less turbulent than our modified Penning discharge, and had no strong radial or axial electric fields imposed on it.

On Tuesday afternoon there was a large poster session of contributed papers on waves and instabilities, including self-organizing processes, which reflected the current interest in plasma turbulence and nonlinear processes. There were many Russian papers in this area. A second session of contributed papers on Tuesday covered the area of generation and dynamics of plasma flows, none of which seemed to be motivated by aerospace applications, but most of them having some obvious relation to commercial materials processing.

On Wednesday morning there were two sessions on plasma chemistry and plasma surface interactions which did not seem to contain anything very new, and all of which seemed to be motivated by industrial applications to integrated circuit fabrication.

On Thursday afternoon there was a surprisingly small session on numerical modeling, leading me to think that not nearly enough of the right kind of work on plasma simulation is being done in the low temperature, relatively high density regime of industrial interest. Also on Thursday

afternoon were many papers on rf and dc glow discharges of a kind used in plasma etching and deposition, again motivated by applications to integrated circuit fabrication.

Mr. Paul D. Spence, GRA on our ONR contract, also attended this conference, and contributed the following: "Two poster papers were of particular relevance to our work on Penning discharge plasmas. The first of these was a theoretical paper by Duk-In Cho and Bong Guen Hong of the Kaist Physics Department in Seoul Korea and W. Horton of the University of Texas, Austin. This paper was titled "Nonlinear Study of Collisional Drift waves in a Partially Ionized Plasma" and is applicable to low β plasmas. Using two fluid theory and including temperature gradient effects, finite heat conductivity, and perpendicular ion viscosity, the authors were able to derive a dispersion relation and growth rate for drift waves. The effect of finite thermal conductivity was shown to increase the growth rate. A temperature gradient was shown to be stablizing for long wavelengths, and perpendicular ion viscosity stabilizing for short wavelengths. These results are directly applicable to the drift wave studies on the Penning discharge. The authors were also able to renormalize the two fluid equations using the direct interaction approximation (DIA) of weak coupling theory. An approximate spectral formula was presented from which an anomalous electron diffusion coefficient and thermal conductivity were derived. These results indicated that the main contribution to transport is due to the low k part of the turbulent spectrum. This result complements our interest in the modification of edge turbulence using active techniques. The second paper was an experimental paper by S. Iizuka, H. L. Pecsel, and J. Jul Rasmussen of the

Riso National Lab, Denmark, entitled "Experimental Investigation of Flute Type Turbulence." The authors investigated spontaneously excited turbulent electrostatic fluctuations due to flute type structures in a low beta Q-machine. The central column of the plasma discharge studied was surrounded by a residual plasma characterized by a large radially increasing D. C. potential. This profile resulted in E x B azimuthal drift. The turbulent electrostatic fluctuations studied were confined radially to a narrow region of this edge plasma where azimuthal velocity shear was maximum. In this region fluctuations were characterized by $e\phi/Te >> n/n_0$ implying that electrons did not maintain an isothermal Boltzmann distribution. This is counter to the common assumption in drift wave studies that electrons do maintain a Boltzmann distribution.

By the injection of an externally excited cell the authors investigated the nonstationary properties of the correlation function for potential fluctuations. The induced uniform convection of the turbulent flow field past detection probes introduced a transient response to the correlation function. A transient increase in the correlation length resulted and hence resulted in a cascade toward longer wavelengths in the energy spectrum. This result may explain some of the inverse cascade observed on our Penning discharge studies under coherent external excitation."

Tour of the JET Fusion Facility

Since 1965, the program committee of this conference has rejected any papers submitted in the field of fusion energy and has excluded high temperature plasma physics and fusion from the scope of the conference.

However, the International Scientific Committee has attempted to keep the conference participants abreast of advances in the field of fusion energy by offering a couple of invited papers on current progress in fusion energy for the information of those attending. On Monday afternoon, F. Leuterer gave a topical invited lecture on "Current Drive n the ASDEX Tokamak with Lower Hybrid Waves." This paper was poorly attended, but reported on one of the major tokamak experiments in Europe, which is a joint effort, located in Germany, by several European countries. International cooperation on the ASDEX experiment extends to the United States, where an international cooperative agreement and an exchange of research personnel are in place, along with partial funding of ASDEX by the U.S. fusion program. This facility is located at the Max Planck Institute for Plasma Physics in Garching, West Germany. It is a D-shaped tokamak, with a major radius of 1.65 meters, a minor radius in the equatorial plane of 40 centimeters, magnetic inductions of up to 2.8 tesla, toroidal currents between 300 to 400 kiloamperes, and it has the capability of up to 2.4 megawatts of rf plasma heating power at 1.3 GHz.

The ASDEX tokamak is noted for being the first to observe the so-called "H-mode" of confinement, in which the plasma confinement time was observed three or four years ago to be about twice that predicted by the phenomenological scaling laws available up to that time. The physical mechanism responsible for this improved confinement in the H-mode has not been identified, but the research program on ASDEX has identified several factors which are associated with this improved containment. These factors include an isolation of the toroidal plasma from the walls and limiter by closed particle drift surfaces, and the maintenance of a very low impurity level in the

plasma. While in the H-mode, experiments have been conducted on rf current drive in the plasma, in which lower hybrid radiation is beamed tangentially in the equatorial plane of the torus, in such a direction as to impart momentum to the electrons that maintain the toroidal current in the plasma. By this means the researchers on ASDEX have maintained the plasma in a quasi steady state, in which all of the ohmic losses of the toroidal current have been made up by momentum transfered by the rf current drive. These researchers have also concluded that in principle it is possible to ramp the toroidal current up from zero without any transformer action whatever in the toroidal plasma, a step which was actually accomplished about two years ago by a Japanese tokamak experiment.

A major issue in the current drive experiments is the efficiency of the current drive, that is, the amps of toroidal current that can be generated per watt of lower hybrid power fed tangentially into the plasma. This current drive efficiency can be expressed as

$$\eta \frac{n_e(m^{-3})I_p(\mathrm{Amp})R(m)}{P_{RF}(\mathrm{watt})}$$

in experiments done in the early 1980's this efficiency factor for a tokamak the size of the ASDEX ranged between 0.1 and 0.2. In the ASDEX experiments, in the H-mode of operation, values of this efficiency factor as high as 0.6 have been observed.

The only other lecture on fusion energy at the conference was delivered by Dr. W. Englehardt, head of one of the experimental group on the JET tokamak at Culham, who delivered a general invited lecture on Friday morning, July 17. His presentation was a curious mixture of encouraging

progress in achieving high plasma parameters in a very large machine, currently the largest in the world, and was discouraging in the very significant areas of physics of which the tokamak community is ignorant. Englehardt mentioned that the JET experiment is now about 1/3 of the way through its overall program, which is currently scheduled to last until about 1991, when the current five-year plan for its operation is scheduled to terminate. It is expected that sometime after 1990, the JET tokamak will burn deuterium and tritium and demonstrate scientific breakeven, that is, more thermal fusion power from fusion reactions, than electrical power needed to maintain the plasma.

The size and plasma parameters of the JET are truly impressive. The toroidal magnetic field is 3.4 tesla over a very large, D-shaped toroidal volume. The toroidal plasma current is five million amperes, with a scheduled increase to seven million amperes being planned. They expect to burn tritium in July of 1991, according to their current schedule of research. Since I heard a similar survey lecture on the JET two years ago, they have added an additional objective to the overall JET program. This is to study alpha particle heating in the plasma when it is burning DD or DT reactions. In this respect, it will duplicate the objectives of the Compact Ignition Torus, an experiment being designed in the United States to replace the TFTR at Princeton and the objective of which is intended to study burning fusion plasmas. The JET tokamak will be much better positioned to study alpha particle heating and burning plasmas, not only because it is a much larger device than the CIT could be, but because the JET facility has a sufficient stored energy capability to be able to operate the plasma for several 10's of

seconds, whereas the CIT will be limited to no more than 5 seconds of flat top operation.

Throughout his talk, Englehardt gave a rather gloomy, though accurate impression of the poor state of theoretical understanding of tokamak physics. He pointed out that the physical phenomena responsible for the Murakami criterion, which determines the MHD stability of tokamak plasmas in terms of a dimensionless parameter based on the magnetic induction, the safety factor, and the major radius, are not known. This parameter is entirely phenomenological, and was first put forward by M. Murakami of the Oak Ridge National Laboratory. The physical basis for this stability criterion is not understood, and Englehardt made no attempt to hide this fact. neither did he make any attempt to hide the fact that the best scaling law for the confinement time in tokamaks, the Kaye-Goldston scaling law, was also phenomenological and that they did not understand the basic physics of the radial transport process by which the particles get from the inside to the outside of the plasma. In this, they are not different from the rest of the tokamak fusion community, but he was unusually forthright about the lack of understanding of basic physics.

There were some other aspects of his talk, however, that suggested that the JET group was unusually weak in fundamentals. One of their problems is the confusion between the particle and energy containment times, and another was their use of the product of kinetic temperature, number density and confinement time as a measure of progress in the field of fusion research. As is well known, and is discussed in Chapter 8 of my textbook, the ion number density, containment time, and kinetic temperature required for a net

power producing fusion reaction can be expressed in the form of a Lawson criterion, a set of curves which is best plotted on a two dimensional representation in which the Lawson parameter, the product of density and containment time, is graphed as a function of the kinetic temperature of a particular fusion reaction, and for a particular powerplant efficiency and other engineering characteristics. About 10 years ago, under pressure of a suggestion by Rand McNally, formerly of Oak Ridge, some members of the fusion community started using the product of number density, containment time and kinetic temperture in discussing the relative status of various fusion experiments, or in comparing the current parameters of a particular machine with the product of these three parameters needed to achieve net power producing fusion reactions according to the Lawson criterion. This product of three parameters is more a public relations than a physics or engineering parameter, since it does not result from any basic consideration of powerplant energy flows or the basic physics of fusion reactions. In spite of this defect, the talk by Englehardt used the product of these three plasma parameters in a very naive way, which suggested that they were unaware of some of the basic power balance considerations which must apply to fusion powerplants.

The third major event relating to fusion energy associated with the conference was a trip to the JET facility at Culham, which happened to be very nearly on a direct line between Swansea and the London airports. This trip was scheduled for Saturday, the day after the conference. Two bus loads, each containing about 50 people, had signed up for the tour of the JET facility. After a ride of approximately three hours, the conference participants arrived at the JET facility and were taken on a walking tour during which the major

APPENDIX K

Media Stories Featuring the ONR Research Program and the UTK Plasma Science Laboratory

The Knoxville News-Sentinel

Knoxville, Tenn. 37901, Thursday Evening, August 9, 1979

UT Scientists Find New Radio-Wave High-Temperature Plasma Emission

Two UT Knoxville scientists have discovered a new radio emission from plasma which may have significance to the communications, radar and microwave *cooking industries*, an international physics journal reported this week.

Plasma is the electrically neutral gaseous state that matter reaches when heated to a very high temperature. The finding is said to be somewhat similar to the discovery of another elementary particle in physics.

Dr. Reece Roth and Dr. Igor Alexeff say the finding, which they have named "geometric mean plasma emission," is a previously unrecognized mechanism by which plasmas can emit electromagnetic radiation. Details of the work appear in the current issue of "Physical Review Letters," a weekly publication of the American Physical Society.

The researchers say their discovery is of a basic scientific nature and its application to the communications or other industries would depend on how efficient plasma is in generating these radio frequency (RF) emissions. Roth and Alexeff have not yet addressed the efficiency question.

Roth and a colleague, Raghu Mallavarpu, collected the information on the RF emission when they were scientists at the National Aeronautics and Space Administration's Lewis Research Center in Cleveland, Ohio. When Roth came to UT in 1978, Alexeff formulated a theory to explain the data. Both Roth and Alexeff are professors in UT's electrical engineering department.

Roth said emissions from 65 to 350 megahertz were produced by the plasma in the first experiments.

"Frequencies in this range are used for FM and TV broadcasting. This mechanism should be capable of operating over a much wider range of frequencies, including those used for microwave ovens and space communications," he said.

The researchers said the emission could be used as a heating mechanism in nuclear fusion, an area both have worked in for many years. The new emission mechanism may advance research in fusion, which holds the promise of producing large amounts of energy at low fuel costs, they said.

Plasma Radio Emission Research Funded at UT

Dr. Reece Roth, visiting professor of electrical engineering at UT, has received a grant and equipment valued at $250,000 from the Office of Naval Research to study a new form of radio emission from plasma.

Roth will study how plasmas emit electromagnetic radiation. This new form of emission, called "The Geometric Mean Plasma Emission," was first observed by Roth when he was a scientist for NASA's Lewis Research Center, Cleveland, Ohio. The equipment for research here will come from NASA's Cleveland facility.

Plasma is a high-temperature electrically charged gas. The sun and the gas in a fluorescent light tube are plasmas.

New Source of Radio Emissions from Plasmas

Basic Research with High Potential for Useful Applications

The research may open a door to a more comprehensive understanding of plasma behavior and possible uses.

■ By combining experimental and theoretical expertise, Drs. J. Reece Roth and Igor Alexeff of the Department of Electrical Engineering of UTK's College of Engineering have uncovered a previously unrecognized mechanism for electromagnetic emission from superheated gases, called plasmas. Although the discovery represents an advance in basic research, it also holds potential for practical uses. The new radio emissions may well improve the efficiency of devices used for microwave cooking, radar, and communications.

Geometric Mean Plasma Emission

Dr. Roth's observation of the new electromagnetic emission process occurred during a systematic study of electric field dominated plasmas at the National Aeronautics and Space Administration's (NASA) Lewis Research Center in Cleveland. Using a test device called the Bumpy Torus, Roth and NASA colleague Dr. Raghuveer Mallavarpu observed the frequency and intensity of radio waves from a plasma of deuterium (an isotope of hydrogen) gas. Matter reaches the plasma state when heated to very high temperatures so that atoms exist as free electrons and positively charged ions. Plasmas in nature are common; the sun and other stars are in a plasma state. One common commercial use of a plasma is in the flourescent light tube.

When a plasma is placed in a magnetic field under specific conditions, instabilities occur and produce *electromagnetic emissions*. Prior to Roth's experiments, about six

ROTH

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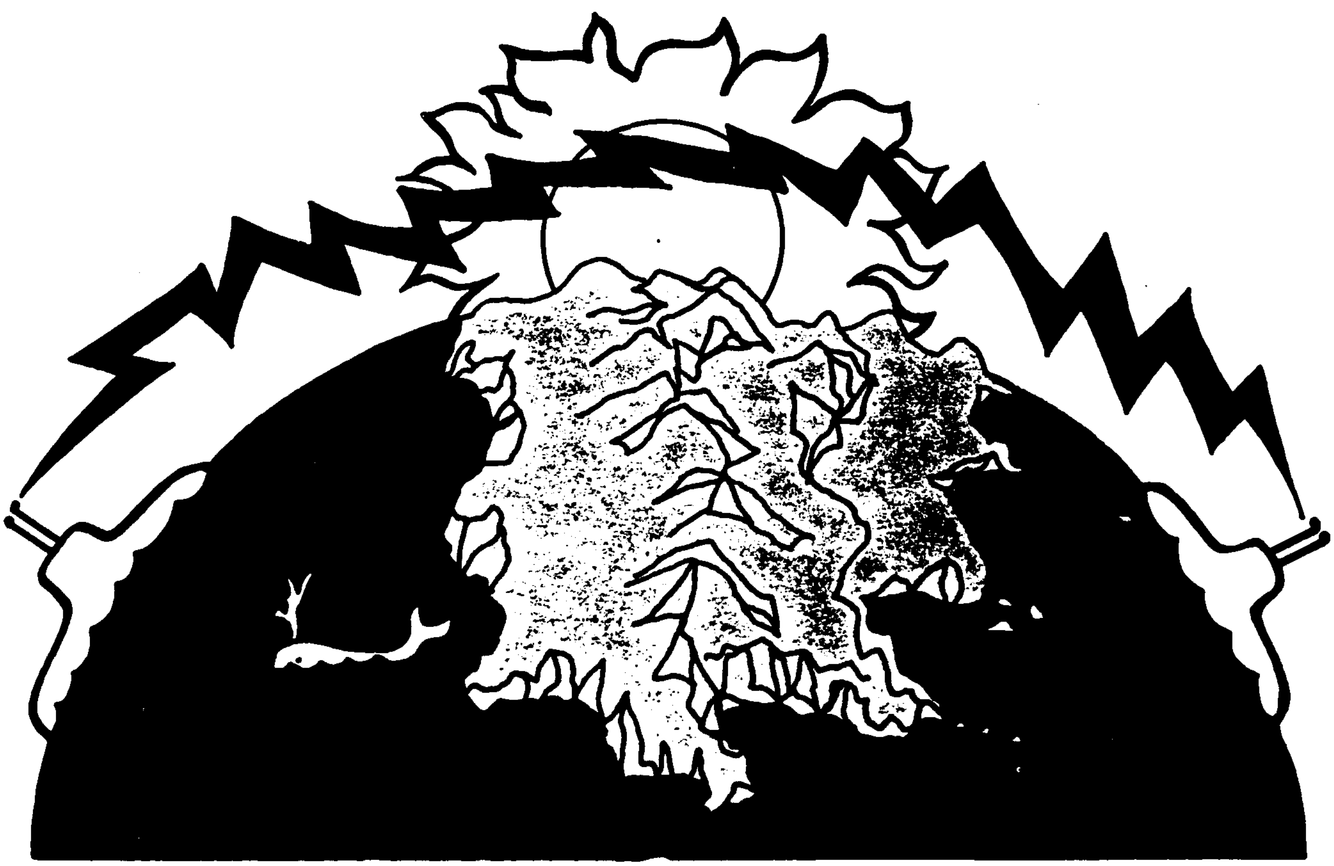
emission mechanisms for plasma had been identified. Roth noted that, "This addition to such a small number is a relatively large percentage increase in our knowledge of this area of plasma physics."

Well-known theoretical models of plasma behavior allowed him to anticipate several of the peaks in the emission spectrum he observed. However, a peak at 65 megahertz was unexplained by existing theory. Continued experiments produced peaks in frequencies ranging from 65 to 350 megahertz. The initial peaks were about one-tenth of a watt, a small but significant power level.

When the experiments were called to the

For a given amount of usable energy, the emission mechanism pioneered by Roth and Alexeff offers promise of smaller, more precise devices that consume less power.



attention of Dr. Alexeff, he formulated a theory both to explain the phenomenon and enable researchers to predict the behavior of the electromagnetic emissions under varying conditions. The proposed mechanism for the phenomena is called the geometric mean plasma emission.

By describing the plasma in the Bumpy Torus experiments as a series of Penning discharges with interpenetrating electron beams, the experimenters were able to calculate the geometric mean frequency for the emissions. The theoretical calculations and the experimental results showed excellent agreement.

Although the theoretical mechanism fits well with one set of peaks experimentally observed, there are others for which no explanation currently exists. Thus, according to Dr. Roth, "The geometric mean plasma oscillation may be only the first of several new emission mechanisms to be identified in electric field dominated plasmas." The research may open a door to a more comprehensive understanding of plasma behavior and possible uses.

Using the Energy of Plasmas

Although experiments so far have shown emissions in the 65 to 350 megahertz range, Drs. Roth and Alexeff anticipate that this range can be considerably extended, both above and below these frequencies. Additionally, the experimental equipment for producing the emissions shows promise of a relatively straightforward transformation into practical devices for industrial and commercial use. Too, the basic phenomenon itself has certain inherent advantages over current means of producing electromagnetic radiation at similar frequencies. All of these factors add up to give the new emissions a high potential for uses ranging from more efficient microwave ovens to more effective radar transmitters.

Roth and Alexeff listed numerous advantages of the new emission mechanisms. The emissions are strong. The frequency can be varied, by controlling the type of background gas used in the plasma and the density of the gas, over a potential range of 10 to 2000 megahertz. Traveling wave tubes, one usual method of generating radio frequency energy, are very inefficient. However, the longer lifetime of the electrons in the geometric mean emission process may permit much greater efficiency, not only in terms of total power used to produce a given radio frequency power, but in that power may be producible in a smaller space as well.

Geometric mean plasma emissions have furthur advantages. The emissions appear at relatively precise frequencies rather than over very broad ranges of frequencies.

The uses of the microwave region of radio frequency energy have expanded rapidly in the space age. Space communications, radar, and telemetry are only a few of the uses which are enhanced by using microwave energy that can penetrate the earth's ionosphere without appreciable interference. Microwaves also have heating properties that have been put to use in food preparation. The result was the microwave oven.

For a given amount of usable energy, the emission mechanism pioneered by Roth and Alexeff offers promise of smaller, more efficient devices that consume less power. When commercially developed, these devices should also result in more reliable operation.

Other Uses of Plasma Emissions

Roth and Alexeff also foresee possible uses for the geometric mean plasma process as a heating mechanism in nuclear fusion. The same process that produces the geometric mean emissions also results in very high plasma resistivities, higher than any other known to occur in plasmas. The high plasma resistance makes it a relatively easy matter to heat the plasma to the high temperature of fusion interest. Unlike nuclear fission as a means of generating electrical power, fusion offers a greatly reduced danger of radiation, according to Dr. Alexeff. When practical means of producing and containing nuclear fusion are fully developed, we may have access to large amounts of power at low cost. The geometric mean plasma emissions may help advance research in this direction.

There may be also applications of this plasma emission mechanism in low frequency communications. These frequencies, at and below the standard AM broadcast band, are widely used for a variety of communications where it is an advantage to have waves closely adhere to the earth's surface. With enough power, such waves can be made to go completely around the earth. Navigation, weather, time standards, submarine communications, and numerous other services use these frequencies.

Through the emission mechanism discussed by Alexeff and Roth, it may be possible that electrons in the lower ionosphere can be excited by solar flares and emit at these low frequencies, thus interfering with low-frequency communications. Proper understanding of the emission mechanism may help in predicting and avoiding such interruptions of communications.

The potential applications of the new knowledge will not be immediate, for there is still much research to be done. Higher power levels need to be generated, requiring further development of the emitter configuration. Research using different ionic species in the emitting plasma needs to be conducted to verify further the theoretical mechanism and to test possibilities for applications. Finally, currently unexplained emissions require further investigation to improve our overall understanding of plasmas. Roth and Alexeff are continuing their work in this area of promise both to technology and to basic science.

The work of Roth and Alexeff has provided one of those rare instances in which research provides us with two windows at once, one a view of imaginative uses of a discovery, the other a deeper penetration into the basic nature of things.

In related work, Dr. Alexeff recently reported generating microwaves with a MASER, a Microwave Amplifier using Stimulated Emission of Radiation. Again using a plasma, Alexeff and research associate Fred Dyer recorded wavelengths of two millimeters, with calculations showing that radiation wavelengths as short as a tenth of a millimeter should be present.

Their work may well improve the state of the art of radar, since the MASER device is a powerful source of mircowaves. According to Alexeff, "The first time we measured a three centimeter wave, we recorded 100 times the power pulse of our test klystron," the more standard vacuum tube source of microwaves.

Not only does the work show promise of more efficient microwave generation, it also may extend the range of radar into the region between conventional radio frequency waves and the visible light spectrum. This region offers the possibility of radar with much greater resolving power.

Alexeff, a UTK professor since 1971, received his Ph.D. from Wisconsin in 1955. His work has taken him to Japan, Brazil, India and South Africa on visiting professorships. Roth, a visiting professor at UTK, was with NASA's Lewis Center for fifteen years and received his doctorate from Cornell. Their work on plasma emissions has been supported by NASA, the National Science Foundation, and UTK. Although early experimental results were reported in several NASA reports, the explanation of the emission mechanism first appeared in a 1979 issue of *Physical Review Letters*.

The work of Roth and Alexeff has provided one of those rare instances in which research provides us with two windows at once, one a view of imaginative uses of a discovery, the other a deeper penetration into the basic nature of things.

Short Takes

Radio emission

A researcher at UT has received a grant from the Office of Naval Research, and equipment valued at $250,000 to study a new form of radio emission from plasma.

Reece Roth, visiting professor of electrical engineering at UT, will conduct experimental studies to test a recently formulated theory of how plasmas emit this form of electromagnetic radiation. First-year funding of what is expected to be at least a three-year study is $35,000.

The new form of electromagnetic emission, called "The Geometric Mean Plasma Emission," was first observed by Roth when he was a scientist for the space agency's Lewis Research Center in Cleveland, Ohio. The equipment UT is to receive is from National Aeronautics and Space Administration's Cleveland facility.

A theory to describe the physical mechanism responsible for this emission was formulated with the collaboration of Igor Alexeff, a UT electrical engineering professor. Details of the discovery were described in a recent issue of "Physical Review Letters," a publication of the American Physical Society.

Milan Mirror
March 12, 1980

UTK Researcher Receives Grant

A researcher at the University of Tennessee, Knoxville has received a grant from the Office of Naval Research and equipment valued at $250,000 to study a new form of radio emission from plasma.

Dr. Reece Roth, visiting professor of electrical engineering at UTK, will conduct experimental studies to test recently formulated theory of how plasmas emit this form of electromagnetic radiation.

In plasma, atoms exist as free electrons and positively-charged ions when heated to very high temperatures. The sun is a plasma, as is the gas in a fluorescent light tube.

The new form of electromagnetic emission, called "The Geometric Mean Plasma Emission," was first observed by Roth when he was a scientist for the space agency's Lewis Research Center in Cleveland, Ohio. The equipment UTK is to receive is from NASA's Cleveland facility.

A theory to describe the physical mechanism responsible for this emission was formulated with the collaboration of Prof. Igor Alexeff of UTK's electrical engineering department. Details of the discovery were described in a recent issue of "Physical Review Letters," a publication of the American Physical Society.

The discovery may have significance to the communications, radar, and microwave cooking industries if it is found that plasmas can produce this new emission efficiently, Roth said. Emissions observed in the Cleveland experiments were in the range of 65 to 350 megahertz, which includes the FM broadcast band.

Roth said it is possible that the same physical mechanism which produces this emission could be used as a plasma heating scheme for nuclear fusion, which many scientists consider the ultimate source of clean, safe energy. He expects to have preliminary information from the experiments by late summer.

Page 4 The Knoxville News-Sentinel Saturday, January 10, 1981

UT Professors Recognized by Engineers Institute

Dr. Igor Alexeff and Dr. J. Reece Roth, electrical engineering professors at UT, have been elected Fellows of the Institute of Electrical and Electronics Engineers.

Alexeff, a professor at UT since 1971, was cited for his research in plasma engineering and thermonuclear fusion. He is a graduate of Harvard University and holds a doctorate degree in nuclear physics from the University of Wisconsin.

Roth, who holds a doctorate in engineering physics from Cornell University, was recognized for his work in magnet technology and discoveries in plasma instabilities. He has been with UT for three years.

News In Brief

campus / ut system

Engineering professors honored

Igor Alexeff and J. Reece Roth, UT electrical engineering professors, have been elected Fellows of the Institute of Electrical and Electronics Engineers.

Alexeff was elected for his work on a plasma laser device which could be used for radar in national communications. Using artificial atoms, the device makes the use of radar much more accurate than was possible before. The funding for the project came from the National Science Foundation after the seed-work had been done.

Roth received his citation for his work in the advance of state-of-the-art fusion related super-conducting magnetic technology. He was also cited for discoveries in the field of plasma instabilities.

The fusion related device was built at the National Aeronautics and Space Administration Lewis Research Center in Cleveland, where Roth worked for 15 years before coming to UT in 1978 as a visiting professor. He was the coordinator for the project at the Center.

Recognition of technical innovation is the primary criterion for nomination.

"Both Dr. Alexeff and myself are very gratified at the distinction of election by our peers," Roth said yesterday.

The Knoxville News-Sentinel

Knoxville, Tenn. 37901, Thursday Evening, May 7, 1981

Outstanding UT Faculty, Students Honored at Chancellor's Banquet

Outstanding members of the UT community were honored for their contributions to scholarship, research and leadership last night at the annual Chancellor's Honors Banquet.

Approximately 100 people were recognized at the convocation, hosted by UT Chancellor Jack Reese and held in the University Center.

The 1981 UT National Alumni Association Outstanding Teachers, who receive a $1000 stipend, were announced at the gathering. These teachers, recognized for excellence in classroom teaching, are:

Dr. Robert E. Bodenheimer, professor of electrical engineering; Dr. Dale G. Cleaver, professor of art history; Dr. Roger L. Jenkins, associate professor of marketing and transportation and Dr. Donald C. Kleinfelter, professor of chemistry.

The alumni association's Outstanding Public Service award went to Dr. Don Williams, professor of horticulture. Williams, who will receive $500, serves on the Knoxville Appearance Committee and Knoxville Beautification Board. He also chairs the public information committee of Tennessee Beautiful.

Outstanding Teachers from 1980 announced last June at the alumni association Board of Governors meeting in Gatlinburg also were recognized. They are:

Dr. Edward S. Clark, professor of metallurgical and polymer engineering; Patsy G. Hammontree, instructor of English; Dr. John M. Wachowicz, assistant professor of finance, and Dr. William Bruce Wheeler, associate professor of history.

Citations for Extraordinary Community Service were given to four faculty and staff members. They are:

Capt. Ronald E. Daniel, assistant professor of aerospace studies; Dr. Frank O. Leuthold, professor of agricultural economics; J.C. Thomas, employment investigator in the personnel department, and former Knoxville Mayor Leonard Rogers, associate director of the Institute for Public Service, who retired in February.

Four faculty and three staff members were given chancellor's citations for extraordinary service to the university. Faculty members receiving citations were:

Dr. Luther Kindall, assistant professor of educational and counseling psychology; Dr. Kelly Leiter, professor of journalism; Dr. Madge Phillips, director of the School of Health, Physical Education and Recreation, and Professor William Shell of the School of Architecture.

Staff citation recipients were:

Jeanne Barkley, alumni affairs' coordinator of class reunions; Robert Harrison, head of auxiliary services for the UT Library, and Philip A. Scheurer, dean of student activities.

The Macebearer for 1981-82 is Dr. Eugene Stansbury, Alumni Distinguished Service Professor of chemical and metallurgical engineering. He will carry the mace at all academic functions such as commencement exercises and other academic processions. One of the highest awards conferred on a faculty member, the award represents eminence in instruction, service and research.

Three UT scientists were selected Chancellor's Research Scholars for 1981. The winners of the award's $1000 cash grant are:

Dr. Jeffrey Becker, professor of microbiology, who received a Research Career Development Award from the National Institutes of Health and who has studied peptide transport across cell membranes.

Dr. Kwang Jeon, professor of zoology, who is involved in the study of cell structure, genetics and physiology of large free-living ameobae, or single cell organisms.

Dr. Lawrence Taylor, professor of geological sciences, one of the world's foremost geological researchers on lunar materials and a prime researcher in the space agency's Lunar Sciences Program, who is involved in the study of terrestrial igneous rocks.

Faculty and staff members honored for prominent national and international awards they received during the academic year are:

William K. Stair, acting dean of the College of Engineering; Dr. Carl W. Asp, professor of audiology and speech pathology; Edward H. Zambara, professor of music; Dr. David L. Dungan, professor of religious studies; Dr. Ralph G. Allen, professor of speech and theatre; Dr. Richard E. Rosenthal, associate professor of management science; Dr. J. Reece Roth, visiting professor in electrical engineering; Dr. Bruce A. Tschantz, professor of civil engineering; Dr. David A. Hake, associate professor and director of the Center for Business and Economic Research; Dr. Betty Cleckley, associate dean of the School of Social Work; Dr. Walter C. Neale, professor of economics; Dr. Gerald E. Hills, assistant dean of Graduate Studies and Research, and Dr. Donald F. Hampton, associate professor of office administration.

Two alumni and two friends of the University received awards for extraordinary service to UT:

U.S. Senate Majority Leader Howard Baker, who is honorary national chairman of a drive to raise $1.25 million for the College of Law.

Turner O. Lashlee, who has held virtually every leadership position in UT's National Alumni Association from chapter president to president of the National Board of Governors.

Louis Loef, current adviser to Alpha Epsilon Pi national fraternity and who has been chosen outstanding chapter adviser of the fraternity on three occasions.

B.A. Ward, chairman of the Knoxville College Board of Trustees and a member of the Chancellor's Associates support group.

Three student organizations were recognized for their extraordinary contributions to the campus. They were the Air Force ROTC Arnold Air Society, the Undergraduate Academic Council and Vol Corps.

Five UT seniors were named 1981 Torchbearers at the banquet. The selection of Torchbearer, the highest honor given to students by the University, is based on scholastic achievement, activities, character and service to the University. The 1981 Torchbearers are:

Robin Lea Scalf, a nursing student from Valley Station, Ky., the only female Torchbearer selected this year and vice president of the Panhellenic Council. After holding many offices in her social sorority Zeta Tau Alpha as well as Panhellenic, she received the 1980 Most Outstanding Junior Greek Award. She chairs the degrees and programs committee of the Academic Council, is vice president of the Undergraduate Alumni Council and chairs the Student Disciplinary Board.

John Steven Handler, a mechanical engineering major from Oak Ridge, who served the Student Government Association as vice-chairman of the Undergraduate Academic Council and as election co-commissioner. He has served on the Student Senate, the Student Judiciary Board and the Dean's Advisory Board. He is vice-chairman of the UT chapter of the American Society of Mechanical Engineers.

Samuel Mountain Hung, 9537 Gulf Park Drive, a college scholar and honors history major who has served as president pro tem of the Student Government Association and as chairman of the Undergraduate Academic Council. He has also served on the Dean's Advisory Council, the Faculty Senate Executive Committee, the history department's Undergraduate Program Committee and the Phi Beta Kappa Book-of-the-Quarter Committee.

Joseph Bruce Kennedy, 5212 Green Valley Rd., a college scholar in economics who is chairman of the Student Government Association Undergraduate Academic Council. He has served on the Faculty Senate Executive Committee, the College of Liberal Arts Scholarships and Honors Committees, the 1981 Chancellor's Honors Banquet Planning Committee and All Campus Event Committee.

J. Scott Rose, an English major from Morristown, president of Omicron Delta Kappa honor society and resident assistant of Reese Hall. He was a Student Government Association senator and chairman of the Student Disciplinary Board. He also was on the Liberal Arts Curriculum Review Committee and a Student Orientation Assistant.

The Knoxville News-Sentinel, Wednesday, September 14, 1983

metro briefs

Computer Added

UT students doing research at UT's Plasma Laboratory will work with a computer to handle information on their experiments. The Office of Naval Research, primary sponsor of the laboratory's research, has provided an additional $30,000 grant to purchase a mini-computer for data handling.

News in Brief

'Who's Who' selects Roth

J. Reece Roth, UT professor of electrical engineering, has been selected for inclusion in the 43rd edition of *Who's Who in America*.

Roth has taught at UT since 1978. While working at NASA's Lewis Research Center from 1963-78, Roth made pioneering contributions to fusion-related superconducting magnet technology.

Engineering wins Defense program

By Melanie Robinson
Daily Beacon Staff Writer

While some are criticizing research for adversely directing university energies outward, one UT professor is praising it for bringing resources into higher education.

Last week the electrical engineering department was notified of its selection to participate in the Department of Defense University Research Instrumentation Program. The department's request for $234,000 to buy research equipment was chosen from more than $1 billion in proposals from universities conducting research of interest to national defense.

J. Reece Roth, professor in electrical engineering, said the benefits reaped from research contracts has enabled his department to update obsolete equipment, thus increasing the value of the electrical engineering degree.

Until a few years ago the department was typical of others across the nation. But because of money received from research contracts and equipment donations from the Defense Department, the electrical engineering department has vastly improved its inventory, Roth said.

As a result of outdated equipment, many graduates received extra training from employers. Because the Defense Department hires many electrical engineering graduates, including UT's, the situation had to be remedied, Roth said.

"The problem got so bad five years ago Washington realized something had to be done. They instituted this program to bring their contractors up to date," Roth said.

In addition, the electrical engineering department receives free, slightly outdated research equipment from government labs and arsenals. The department has accumulated about $1 million in surplus equipment from the Defense Department.

Without the funds and equipment supplied through research contracts, Roth said his department would do without equipment vital to research because the university does not give ample support.

"UT gives us floor space, water and electricity. That's it," he said.

Roth said electrical engineering research contracts have brought in about $1 million dollars in recent years, but UT keeps a substantial portion to pay for secretarial costs and other expenses. When the department receives equipment grants, no overhead costs are kept by UT.

Most of the money from the new award will go to buy a $170,000 Microwave Network Analyzer.

Not only students will benefit from the new equipment, but also the community, Roth said.

"In addition to our students getting experience with state-of-the-art equipment, the technology of the whole area will be elevated because information will be carried to employers," he said.

A12 KNOXVILLE JOURNAL Thursday, March 13, 1986

CITY/STATE DIGEST

Air Force awards contract to UT

The U.S. Air Force has awarded the University of Tennessee's College of Engineering's Plasma Laboratory a $600,000 contract for research in plasma, fusion and microwave emissions. The research will include work toward the development of fusion energy, according to a university spokesman. The three-year contract also provides for undergraduate research assistantships in the summer.

Engineering Update
THE UNIVERSITY OF TENNESSEE, KNOXVILLE
COLLEGE OF ENGINEERING
VOLUME 3/ISSUE 1/WINTER-SPRING 1

THE UTK PLASMA SCIENCE LABORATORY

Course offerings and active research in the field of plasma science ve been underway at The University of Tennessee, Knoxville, since 1970. The UTK plasma science laboratory was set up in its present form in 1980, within the electrical engineering department.

Since 1980, the laboratory has been partially supported by contracts with the Office of Naval Research, the Air Force Office of Scientific Research, the National Science Foundation, and the Tennessee Valley Authority. In calendar year 1985, the total budget of the UTK plasma lab was approximately $473,000. The laboratory focusses its research efforts on steady-state, electric field-dominated plasmas. Our emphasis on steady-state plasmas makes it relatively easy to take diagnostic data of high quality and to vary parameters in an exploratory way to identify and study the physical processes which occur in these plasmas. The emphasis on electric field dominated plasmas (those plasmas having strong radial and/or axial electric fields penetrating them) has allowed us to focus on an area of plasma science which has been neglected by other university research groups. Particular electric field dominated plasmas under study in the plasma science laboratory include the orbitron maser, which is of interest because of its capability to produce sub-millimeter microwave emission at power levels in excess of one watt; and plasmas generated by Penning discharges, which are highly turbulent and provide a convenient test bed for research on plasma turbulence and collisional magnetic pumping as a plasma heating technique.

The laboratory is equipped with a variety of operating plasma diagnostic instruments and a large inventory of power supplies, electronic test equipment, and communicaitons related electronic equipment which support our exploratory research efforts. There are also several inexpensive-to-operate steady-state plasmas on which diagnostic instruments can be veloped and debugged and on which data of unusually high quality n be taken with existing instruments.

The laboratory acquired in 1980 approximately $400,000 of pla related instrumentation from the NASA Lewis Research Center, w enabled us to begin our research program on electric field-domin plasmas. This inventory of laboratory equipment has been suppleme over the last three years by used but serviceable surplus equipment tained from Department of Defense installations.

A recent grant (FY 1985) of $233,000 from AFOSR under the D University Research Instrumentation Program has allowed us to purch state-of-the-art radio frequency network analyzers and electronic test eq ment which not only provides our students training with the latest equipment, but also makes it possible for us to take plasma diagno data of a quality and kind that is possible to very few other university ba research laboratories.

The UTK plasma science laboratory now has one of the best-equip university facilities in the country for the steady-state, quantitative meas ment of plasma emissions over a wide frequency range, and for measurement of plasma turbulence in the form of electrostatic poten and number density fluctuations over a wide dynamic range and a wide range of frequencies. Our inventory of research equipment includes computerized data handling and processing equipment wh is connected to the electrical engineering department's VAX comp for on-line data analysis. Over the past five years, we have pioneered the development of software programs for the analysis of data fr Langmuir probes, retarding potential energy analyzers, charge excha neutral energy analyzers, and electrostatic turbulence and microwave s tering data.

Oversight of the plasma science laboratory research is conducted Professors J. Reece Roth and Igor Alexeff.

Context
THE UNIVERSITY OF TENNESSEE, KNOXVILLE
A PUBLICATION FOR THE UNIVERSITY COMMUNITY VOLUME 3 NO. 11 APRIL 2, 1986

Roth, Alexeff Get $600,000 To Develop High Resolution Radar

Two UTK scientists—working at the frontiers of radar and communications research—have been given a $600,000 grant to pursue their studies about the way plasma affects microwaves.

For almost a decade, Dr. Igor Alexeff and Dr. J. Reece Roth have been studying microwave emissions generated when materials are superheated beyond the liquid and gaseous states to become plasmas. The material inside a fluorescent light tube is a plasma, as are the sun and all stars.

The three-year contract from the Air Force Office of Scientific Research will provide $200,000 annually for Alexeff and Roth, professors of electrical engineering, to do basic research that could lead to a new generation of high resolution radar and to improve communications between earth and voyaging space vehicles. Their work also has potential applications for fusion energy research, sophisticated welding and laser systems, and in the "Star Wars" defense plan.

Tim Elledge

Dr. Igor Alexeff

"Plasmas could be useful as a jamming tool," Roth said. "They produce a broad band of radio frequency emissions, all the way from the lower end of the AM radio band up to 1.2 gigahertz, which is far above most television channels."

Plasma is the key ingredient in what scientists view as the ultimate energy source—fusion. If a hydrogen isotope, found in seawater and called deuterium, is heated to the plasma state, it produces a tremendous amount of energy without the radiation side effect of fission nuclear reactors, Alexeff said.

Princeton University scientists have achieved fusion reactions for a few tenths of a second but do not yet fully understand how ions move in plasma. Once controlled fusion is developed, a reaction fed by seawater would be perpetual, like that of the sun, producing vast amounts of energy, the engineers say.

Alexeff and Roth, who have collaborated since 1978 in their Ferris Hall laboratory, also are interested in how plasmas block radio frequency waves and how signals might be pushed through them. Plasmas generated by the heat of reentry into the earth's atmosphere block communications from space vehicles.

"By looking at the way the radiation is absorbed," Roth said, "We can tell how frequently the electrons are colliding and how momentum, or energy, is removed from the electrons."

The grant also provides for summer internships each year that will permit nine undergraduate engineering and physics students to work in the Plasma Laboratory. Roth said the grants of $2,000 each were established to acquaint students with research so they might consider graduate studies after they receive their undergraduate degrees.

Tim Elledge

Dr. Reece Roth

The Knoxville News-Sentinel, Monday, April 13, 1987

tennessee news

Maser draws scientist across half a world

Chinese professor watches work at UT

by JAY DISKEY
News-Sentinel staff writer

J. Miles Cary /News-Sentinel staff

Liu Shenggang, Chinese scientist, is visiting the University of Tennessee.

Not many people travel halfway around the world to study synthetic atoms in a small metal cylinder, but Liu Shenggang did and he says it was well worth the trip.

Liu, a 56-year-old scientist from Chengdu, China, is visiting the University of Tennessee for two weeks to study Dr. Igor Alexeff's Orbitron microwave maser — a small metal device that is expected to usher in a new era in electronic communications.

The device may also spark an exchange of professors between UT and the Chengdu Institute of Radio Engineering, said Liu and Alexeff, a UT professor of electrical engineering who invented the Orbitron.

What Liu learns in Alexeff's Ferris Hall laboratory he will take back with him to Chengdu, the Chinese professor said.

"I'm very interested in the subject," Liu said of Alexeff's Orbitron maser. "Its applications are very wide."

Alexeff's maser — a microwave amplifier using stimulated emission of radiation — can produce microwaves of a higher frequency than had been thought possible before. Such waves are commonly used to transmit radio and telephone signals.

Military personnel and aviators are interested in the device because it will provide sharper radar images of objects. The Orbitron will also make for more compact radar units, said Alexeff, who is arranging for sale of the device to a commercial firm.

"It is the next generation of microwave tubes for radar," he said.

Earlier this week the Institute of Electrical and Electronics Engineers Inc. named Alexeff the outstanding engineer in the Southeast because of his contributions to microwave technology and the invention of the Orbitron. Alexeff is the founder of the Tennessee Inventors Association.

Liu, the youngest member of China's prestigious Academy of Science, met Alexeff at a conference in Florida several years ago.

He had to obtain special permission from his government to travel to the United States to visit Alexeff at UT, he said. The trip took him a year and a half to arrange.

Since arriving at UT Liu has spent most of his time in Alexeff's lab. Before he leaves for California Tuesday he will lecture to physics and electrical engineering students at UT.

Liu said American students are active and energetic. "But they don't take as many classes as the Chinese students do," he said.

Liu teaches microwave electronics at the Chengdu Institute, which is located in southwest China about 1,500 miles from Beijing. The school has about 8,000 students.

Alexeff said he is hoping to set up a professors exchange between UT and the institute in Chengdu. The exchange will have to be approved by UT administrators, Alexeff said.

"This visit is a very good opportunity to promote future exchange," Liu said.

THE DAILY BEACON

Vol. 48, No. 10 University of Tennessee, Knoxville Friday, July 8, 1988

Grants help profs in research

Ion implantation may protect tanks from corrosion

By MARY WAID
Daily Beacon Staff Writer

Two UT engineers are hard at work for the university and the U.S. Army.

J. Reece Roth and Raymond Buchanan, both professors in the College of Engineering, have been awarded a $20,000 grant from the Army Research Office.

The grant is to investigate whether plasma ion implantation can help prevent metal corrosion.

"The official starting date (of the research) was July 1," Roth said. "We were notified of the award about the third of June."

"This was a program called the Short-Term Innovative Research Program, which was sponsored by the Army Research Office," Roth said. "In our area, which was natural sciences, there were 199 proposals, but only four awards were granted... we are pleased that our submission was chosen."

Roth and Buchanan's idea of plasma ion implantation would be ideal for stopping corrosion in army tanks and battlefield equipment.

The method involves placing metals in plasma. The plasma is a hot, ionized gas. If the metal is at a high negative voltage, ions are drawn out of the plasma and are, in turn, implanted on the surface of the metal.

Corrosion usually is prevented by galvanizing or painting metal parts, but the materials that have to be used in these methods are not as durable as materials that corrode.

"It would be more expensive than painting or galvanizing... it would never be competitive on that level," Roth admitted. "However, it would be cheaper and more effective than ion beam implantation."

"It would be economically feasible, and it might make sense to use it on things such as gear teeth and turbine blades," Roth continued. "There are many such aerospace applications that would make it economical to use the plasma ion implantation because of the parts."

"The ion beam implantation can't be used on such things as gear teeth or screw threads... beam implantation is very expensive and its uses are limited. Plasma ion implantation can be used on small and complex surfaces," Roth explained.

"We're off to a satisfactory start," Roth said. "We already have a plasma apparatus set up and in operation. We have to make a few pieces of high voltage switching, and we hope to have some exposed by September 1."

"The work we are doing for the Army will be completed by December," Roth said. "After that, we will submit a proposal to the Army for a three-year study."

Roth and Buchanan will conduct these experiments at UT's Plasma Science Laboratory.

Context

THE UNIVERSITY OF TENNESSEE, KNOXVILLE

A PUBLICATION FOR FACULTY AND STAFF VOL.6, NO.3 OCTOBER 13,198

Can Plasma Ions Stop Metal Corrosion?

If two UT Knoxville engineers are successful, the U.S. Army may never again have to worry about corrosion in tanks and other battlefield equipment.

Drs. J. Reece Roth and Raymond Buchanan, professors in the College of Engineering, have been awarded a $20,000 grant from the Army Research Office to investigate whether plasma ion implantation will inhibit metal corrosion.

The work also is funded by UTK's Center for Materials Processing and the Department of Materials Science and Engineering.

The method involves placing metals in plasma, which is a hot ionized gas. If the metal sample is at a high negative voltage, this draws ions out of the plasma and implants them on the surface in a thin layer that prevents corrosion of the metal.

Corrosion is usually prevented by galvanizing or painting metal parts. When that is not possible, metals or alloys that inherently resist corrosion are used. The drawback is that materials often have to be used that, while resistant to corrosion, are not as durable or as hard as materials that corrode.

"Plasma ion implantation, at least for the forseeable future, would be expensive compared to simple methods such as painting or galvanization," Roth says. "But we think it does have promise for immediate application to things like gear teeth, screw threads and turbine blades."

Plasma ion implantation could replace a related process -- ion beam implantation -- used to protect metal surfaces of prosthetic implants such as artificial hip joints, Roth said.

"Beam implantation is very expensive and its uses are limited. It can't be used, for example, on small or complex surfaces like gear teeth or screw threads. Plasma ion implantation would be much cheaper and works on any electrically conducting surface," he said.

"This new method could be used in a variety of industrial and military applications," Roth said. "The materials that are used now are chosen not because they are best for the job, but because they are corrosion-resistant.

"The Army is interested in plasma ion implanation because it could eliminate corrosion on things like turbine blades, which are used in helicopters, light aircraft, and even some vehicles."

Roth, professor of electrical and computer engineering, and Buchanan, professor of materials science and engineering, will conduct experiments for the research at UTK's Plasma Science Laboratory, which is affiliated with the Department of Electrical and Computer Engineering.